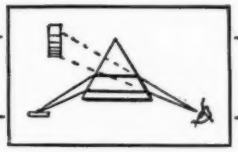
Journal of the OPTICAL SOCIETY *of* AMERICA

VOLUME 26
No. 7



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Published monthly
at Prince and Lemon Sts., Lancaster, Pa.
by the
AMERICAN INSTITUTE OF PHYSICS
Incorporated
175 Fifth Avenue, New York, N. Y.
FOR AND UNDER THE EDITORIAL SUPERVISION OF
THE OPTICAL SOCIETY OF AMERICA

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Journal of the
OPTICAL SOCIETY *of* AMERICA

VOLUME 26 JULY, 1936 NUMBER 7

The Fuertes Observatory Ultraviolet Stellar Spectrograph

R. WILLIAM SHAW, *Departments of Physics and Astronomy, Cornell University*

(Received April 6, 1936)

A new design for a stellar spectrograph which embodies lightness in weight with high rigidity is described. The instrument is composed of three parts: the spectrograph proper, the inner case or "rigidity box," and the constant temperature case. The spectrograph proper is a light weight instrument which may be removed easily from the mounting and used as a laboratory instrument if desired. The "rigidity box" is the member which forms the main support for the spectrograph. The method of mounting is such that the spectrograph proper has a small degree of freedom which minimizes the possibility of small stresses being transmitted to it from mechanical or thermal causes. The constant temperature case is an easily removed cover which provides a second constant temperature air space about the spectrograph and with a triple fan system provides an efficient temperature control for the instrument. The spectrograph is equipped with a slit which eliminates troubles arising from lack of parallelism of the jaws, shifting zero and back-lash. The slit may be opened rapidly to maximum width for intensity calibration without loosing a predetermined slit width. Curves showing the performance of the thermal-control system are given, as well as photographs of the mechanical parts.

THE development of aluminized mirrors for astronomical use has, because of the high ultraviolet reflectivity of these mirrors, made the astrophysical spectrograph with quartz optical parts an important addition to observatory equipment. As in the case of a spectrograph for visual work the chief problems of design are the choice of optical parts suited to the particular investigations to be undertaken and the development of a mounting for them which will be extremely rigid and which will provide for an efficient temperature control.

The optical parts used in the astrophysical spectrograph described in this paper have proved to be admirably suited for problems of ultraviolet stellar spectroscopy after an extended trial in a less elaborate mounting.[1] They consist of a pair of 60-degree Cornu prisms and a pair of crossed crystalline-quartz lenses. The lenses have apertures of one and seven eighths inches and focal lengths of approximately fifteen inches. It was found that this combination of prisms and lenses gave an exceptionally flat field from λ4000 to λ3000 and dispersion from 40 to 16 A/mm. Since this wave-length range includes the new region made available to astronomers by aluminized mirrors, it was convenient to arrange the optical train for a fixed angle of minimum deviation at λ3600. Such an arrangement tends to reduce mechanical difficulties in construction and the possibility of change in adjustment during observations.

The design of a mounting for the optical parts was subject to a number of considerations. It

[1] For the description of an earlier spectrograph utilizing these optical parts see S. L. Boothroyd, Astrophys. J. **80**, 1 (1934); and R. W. Shaw, Astrophys. J. **82**, 87 (1935).

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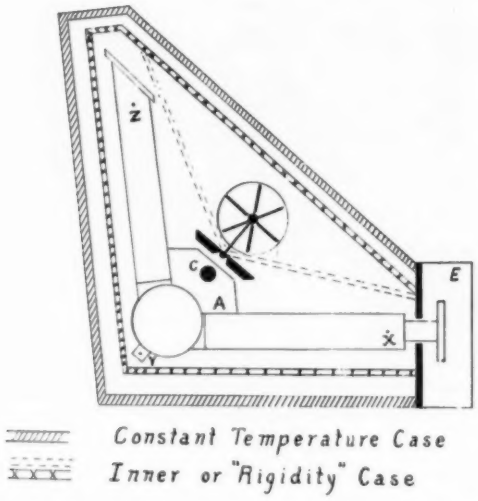

FIG. 1. Schematic arrangement of the spectrograph proper, the "rigidity box," and the constant temperature case.

was planned to use the instrument during part of the investigations on a telescope with a light weight tube; therefore the reduction of weight with maintenance of high rigidity was of major importance. Moreover, since the spectrograph was to be used in a completely open dome at high altitudes, an efficient and dependable temperature control was necessary. In addition to these specifications a more unusual requirement was made. Preliminary investigations in certain problems in ultraviolet stellar spectra showed that it would be very desirable to use the spectrograph in the laboratory in interpretive phases of the work in which it would be helpful to utilize the same dispersion as in the stellar spectrograms. To do this without manual inconvenience arising from the support used in attaching the instrument to the telescope, it was necessary to provide a simple method for removing the spectrograph from its more or less unwieldy supporting and thermal insulating cases.

The problem then was to devise a method for holding a light-weight laboratory spectrograph with adequate temperature control in a mounting which would provide rigid support for all positions of the instrument and yet permit the latter to be removed without inconvenience or change in adjustment.

The complete instrument is composed of three major parts: the spectrograph proper, the inner case or "rigidity box," and the constant temperature case. A schematic arrangement of the parts is shown in Fig. 1. The spectrograph proper consists of the collimator, prisms, and camera mounted on a light steel base braced by the plate *A*. This forms a unit which may be removed readily from the inner case.

The inner case or "rigidity box" is the member which supports the spectrograph while it is on the telescope. It is essentially a triangular box in which the spectrograph proper may be placed and securely fastened. The "rigidity box" is connected to the telescope by a master pin *C* and by a collar or slit housing *E* at the collimator end. The weight of the spectrograph proper is carried by the pin *C* which passes through the plate *A*. Pressure screws acting on the base of the spectrograph at the points *X*, *Y* and *Z* maintain the spectrograph in a fixed plane with respect to the "rigidity box" but allow a very slight movement in that plane to relieve thermal and mechanical strains.

The constant temperature case is a shield of aluminum lined with insulite. It can be slipped readily over the entire instrument while the latter is attached to the telescope. The location of air circulating fans is indicated in Fig. 1.

THE SPECTROGRAPH PROPER

The spectrograph proper is shown in Fig. 1. The collimator, prisms and camera are mounted on a light channel-steel base which forms nearly a right angle since the two prisms are set for minimum deviation at λ3600. The collimator and camera are provided with the usual adjustments for focus and plate tilt. The plateholder may be moved perpendicular to the dispersion in order that a number of stellar spectrograms can be taken on the same plate (50×90 mm). The channel-steel base is strengthened by the steel plate *A*. Through this plate is passed a hollow cylinder *B* which forms the major support for the spectrograph proper. It is through cylinder *B* that the master pin *C* passes supporting the entire instrument at the center of gravity. The spectrograph proper is prevented from rotating about *B*, and is maintained in a fixed plane in the supporting case (Fig. 3) by pressure screws and grooves at the end of the collimator, the end of

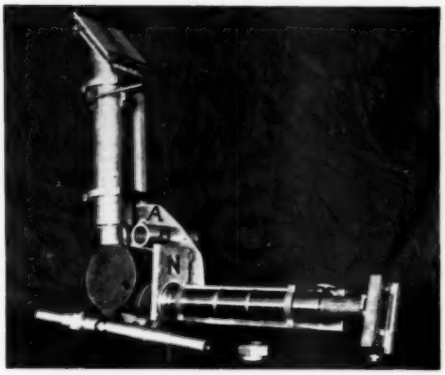

FIG. 2. The assembled spectrograph proper and the master pin with locking nuts.

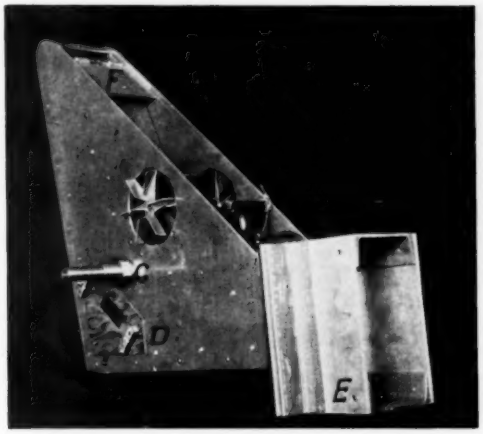

FIG. 3. The inner case or "rigidity box" with master pin inserted and the slit housing *E* attached.

the camera, and near the prisms as indicated by *X*, *Y* and *Z* in Fig. 1. Thus there is achieved for the instrument a three-point support in one plane with the greater portion of the weight carried by the master pin *C*. This method of support gives the spectrograph a certain freedom with regard to thermal expansion of the various parts even though the supporting case is constructed of different materials than the spectrograph proper.

The prisms are covered with a light-tight cap in which is mounted a rotating shutter which makes possible the Hartmann test for focus. The box *N* contains a thin ultraviolet transmitting filter which may be inserted in the collimator beam. A filter of this kind is particularly useful in reducing the intensity of certain portions of the spectrum in intensity calibration.

THE INNER CASE OR "RIGIDITY BOX"

The chief supporting member for the spectrograph proper is shown in Fig. 3. This lightweight case is constructed of two duralumin plates forming the top and bottom and five-inch channel stock serving as the sides. The channel stock is also extended toward the center of the case as indicated by the double dash line in Fig. 1. This arrangement makes the case very rigid with respect to both shearing and crushing forces. The entire box, acting also as an inner temperature case, is securely riveted except for the left side which is held in place by screws.

It is through the removable left side of the "rigidity box" that the spectrograph proper is slipped into place. The master pin *C* is then passed through the hollow cylinder *B* (Fig. 2) and the nuts tightened. Since the cylinder *B* is as long as the case is deep, it acts as a supporting column for the center of the case when the nuts on the master pin *C* are tightened. Such an arrangement not only insures a rigid support for the spectrograph but also effectively counteracts any weakness[2] introduced in the case by cutting an opening for the door *D*, which admits to the optical parts. Rotation of the spectrograph proper about the master pin *C* is prevented by the pressure screws mentioned before. Because of the form of this case and the method of attachment to the spectrograph, it does not transmit to the latter small stresses which may exist in it.

The slit and the collimator end, which must protrude from the "rigidity box" but not touch it, are housed by the box *E*, serving at the same time as a supporting collar for the entire instrument and preventing rotation as a whole about the master pin. This collar is thermally insulated from the inner case, except for the four attaching bolts, by a sheet of Bakelite.

It can be seen that if the doors *F*, through which the camera is loaded, are closed, the

[2] J. H. Dowell, Trans. Opt. Soc. **31**, 226 (1929-30).

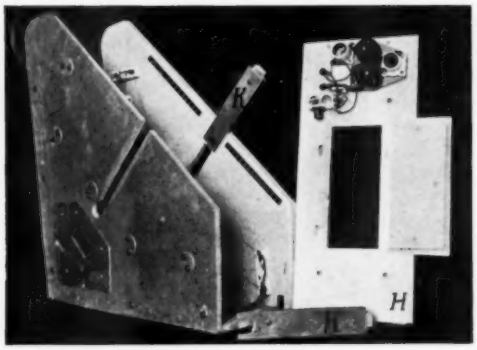

FIG. 4. The constant temperature case with front *H* removed. The sliding strips *K* hold the case on the master pin.

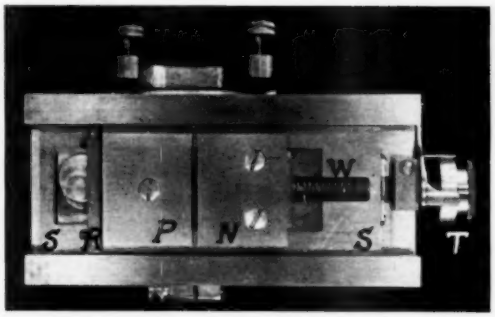

FIG. 5. Spectrograph slit showing the cam used for rapid opening of the slit for intensity calibrations.

spectrograph proper will be held in a completely dead-air space. The form of these doors is such that there is a minimum disturbance in temperature when the plateholders are changed, yet they may be quickly opened wide for inspection or adjustments.

Air circulation about the case is accomplished by the pair of centrifugal fans shown in Fig. 3. A third fan (not shown in Fig. 3, but see Fig. 1) driven by the same motor circulates air on the inside of the "rigidity box" thereby preventing localization of warm air during long exposures. Several small holes have been provided for the slow passage of air from the inner case to the region of the outer fans in order that temperature gradients can not form.

CONSTANT TEMPERATURE CASE

The "rigidity box" is surrounded completely, except for the thermally insulated collar *E*, by the constant temperature case shown in Fig. 4. This case, which forms a single unit with a removable side *H*, is constructed of commercial insulite covered with 1/16-inch aluminum sheeting. The constant temperature case slips easily over the inner case and is held in place by the sliding strips *K* fitting snuggly around the master pin *C*. Small wooden blocks on the inside serve as spacers between the two cases.

The removable side *H*, provided with a door through which adjustments on the fans, motor, etc. can be made, is held in place by four thumbscrews. It carries the bimetallic thermostat and the motor and heating unit switches. Connections are made to the flat heating units (not shown), supported by the porcelain insulators on the inside of the case, by slip connectors. Removal of the side *H* from the temperature case is, therefore, a simple procedure.

A suitable opening *M* in the case gives access to the prisms. This door has a small glass window through which mercury-in-glass thermometers in the inner and constant temperature cases may be viewed.

The constant temperature case provides a space in which air is circulated continuously and heated intermittently as necessary. The construction is so convenient that the entire case may be removed in a few minutes from the instrument without dismounting the latter from the telescope. The only metallic connections which the inner spectrograph has with the outside air are through the master pin and the four bolts which hold the supporting collar *E* to the inner case. The heat losses by the master pin are negligible since it passes through a heated space before reaching the outer air.

THE SLIT

In investigations carried out with this instrument it was found desirable to use the spectrograph itself as the plate calibrating instrument. The intensity marks were produced by placing over the wide open slit a step-diaphragm with a series of openings of suitable widths. Unless many plateholders are available it becomes necessary to place the intensity marks on each

plate soon after the stellar exposure has been made. This means that the slit may be opened wide many times during the night. Such a frequent changing of the slit width is usually accompanied by a wearing of the adjusting screw which tends to change the zero. Moreover in an ordinary slit there are the customary troubles with back-lash and a gradual loss of parallelism of the slit jaws.

These difficulties have been effectively overcome in the slit shown in Fig. 5. The slit plate N (stainless steel) is fastened permanently to a supporting post, part of which may be seen at the right edge of the slit plate. The other jaw P is mounted on a sliding plate S three inches in length. The two jaws are made parallel to each other by the paralleling bar R. Once the jaws have been properly adjusted they will remain accurately parallel indefinitely since very long bearing edges on the sliding plate S are available as compared to the actual motion of the slit plate.

The thumbscrew T pressing against a steel stop on the sliding plate S determines the slit width in the ordinary way. The screw, however, is used merely as a stop against which the spring W pushes the sliding plate. The slit width is actually changed by the cam shown at the left in Fig. 5. This cam, conveniently actuated by a knob on the back of the slit mounting, makes it possible to open the slit at once to a maximum for the intensity step-diaphragm or to relieve the spring pressure on the thumbscrew when changing slit widths. During such changes there is no danger of a zero shift or the loss of a predetermined slit width since the screw acts merely as a stop against which the spring returns the sliding plate. An extended trial period has shown that this arrangement is most satisfactory for rapid opening and closing of the slit.

Rotation of the slit about the collimator is prevented by a collar which also makes it possible to align the slit accurately with the refracting edges of the prisms. A four-degree tilt of the slit plane with respect to the normal to the optic axis has been provided so that guiding may be accomplished by reflected light from the slit edges. No attempt was made to use curved slits since the great range of wavelengths in focus at one time more than equaled any advantage from their application.

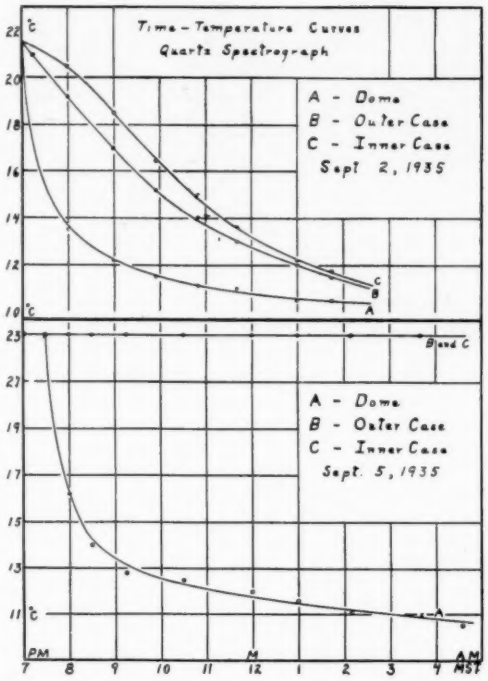

FIG. 6. Time-temperature curves showing the effectiveness of the thermal insulation with the temperature control inactive and active. In the lower graph note that the observations for B and C lie together on the same horizontal curve indicating complete temperature regulation throughout the night.

PERFORMANCE

While this instrument may appear to be unnecessarily complicated, it can be taken apart and reassembled by a person familiar with the parts in one hour. All expectations regarding the rigidity have been realized although the weight of the assembled spectrograph is only 125 pounds. It is therefore easily handled by one individual.

Tests were made for the purpose of detecting possible shifting or blurring of the spectra due to the motion of the fans or motor. While no such effect was found, it seems desirable to replace the plain bearings with self-aligning ball bearings to eliminate the very slight chatter which exists.

The triple fan system and the double case proved to be most adequate in maintaining a constant temperature even under adverse conditions. Typical tests of the temperature control are shown in Fig. 6. The observatory dome

was opened at about 7 P.M., M.S.T. As indicated by the curves *A* the dome temperature changed rapidly during the first two hours. The curves *B* and *C* of the upper graph show the corresponding changes in temperature of the outer and inner cases when the heating units and fans were turned off. It is apparent that the thermal insulation of the spectrograph is quite effective. It should be noted that during this test period plates were being changed from time to time and consequently some cold air entered the spectrograph.

The lower graph gives similar observations when the heating units and circulating fans were in operation. In this instance the temperatures of both outer and inner cases remained within a tenth of a degree of the initial temperature. This is a most satisfactory performance inasmuch as the thermal control used had a sensitivity rating of only one quarter degree and the difference between the dome and spectrograph temperatures became more than twelve degrees.

A comparison of spectrograms with those obtained at a number of large observatories shows that this instrument gives a spectral definition equal if not superior to many of the astronomical spectrographs now in use.

The author wishes to express his appreciation to Professors S. L. Boothroyd and R. C. Gibbs for their interest and encouragement in the design of the spectrograph and to the mechanicians of the physics department for their skill and patience in executing the plans. Grateful acknowledgment is made to the members of the Lowell Observatory staff for the use of a reflecting telescope on which the spectrograph was tested and for their continued interest in all of the problems undertaken.

A Hyperfine Structure Spectrograph

L. P. GRANATH AND R. K. STRANATHAN, *Department of Physics, New York University, University Heights*
(Received April 15, 1936)

A spectrograph particularly suited for work in hyperfine structure is discussed. It consists of a Fabry-Perot etalon and prism spectrograph built as a single unit to eliminate many of the errors introduced when the apparatus is assembled in the usual way.

THE precise determination of hyperfine structures and the calculation of nuclear magnetic moments has become of importance. In the authors' work on the hyperfine structure of caesium, it was found necessary to construct a special spectrograph to meet the needs for precision measurements with the etalon. The apparatus was designed to eliminate as many as possible of the errors in spectroscopic work and to be flexible and convenient in use.

A lathe bed was used as the foundation for the spectrograph, serving as an optical bench upon which the apparatus was mounted. The apparatus is shown in Fig. 1.

The principal advantage of using a lathe bed for a foundation is its rigidity. As all optical parts are firmly mounted on the same heavy foundation any movement of one must be accompanied by a corresponding movement of the whole system. In addition each part can be raised or lowered separately and the distances between parts varied as desired. It is important that the distance between the prism and collimator be variable to provide for the use of two Fabry-Perot etalons in series in case the multiplex is desired. The entire apparatus, with the exception of part of the camera, is enclosed in a constant temperature box. The temperature of the box is controlled by a mercury thermostat and a relay, and is kept constant to about 1/20 degree centigrade. It is not only necessary to keep the apparatus at constant temperature while photographing, but it is also quite important that the etalon be adjusted at the temperature which is to be used. The necessity for this is probably due to unequal changes in pressure on the Fabry-Perot plates applied by the etalon finger clamps upon a change in temperature. The etalon can be easily adjusted at the temperature of the box by rotating the etalon stand until it comes in line with the mercury arc light entering through a shutter opening in the side of the constant temperature box. It is also advisable to use a filter in order to adjust the etalon for parallelism using monochromatic light.

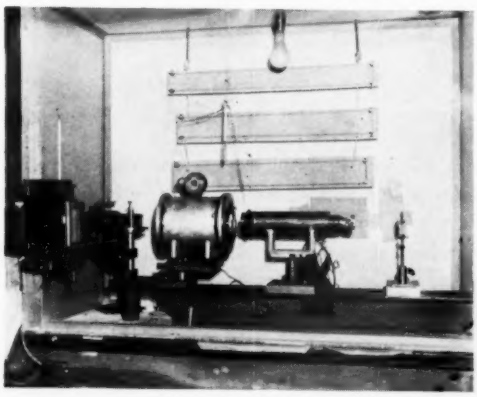

FIG. 1. Spectrograph.

A convenient type of Fabry-Perot mounting[1] is shown in Fig. 2. The etalon plates are held apart by three invar pins mounted in a brass ring. For long spacers the pins are held by two or three such rings. The mount can easily be adjusted to accommodate various size spacers by adjusting the screw legs. Spacers ranging from 0.75 to 25 mm have been used. Fringes can be obtained by machining the invar pins to equal lengths to within 1/400 mm, relying upon the compressibility of the pins to take care of the final adjustment. However, for precision work this is not at all satisfactory. The fringes become much sharper when the pins are polished to equal lengths by the use of rouge or No. 05

[1] This type of Fabry-Perot holder was previously used at Washington Square College.

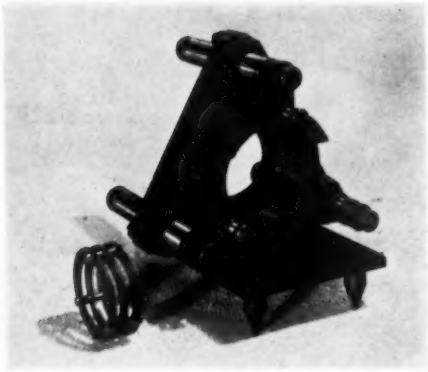

FIG. 2. Fabry-Perot mounting.

emery paper. By using spacers, polished to equal lengths within a wave-length of light, small separations have been observed that were completely blurred before extreme care was used in polishing.

The apparatus for testing the spacers is shown in Fig. 3. It consists of a telescope and collimator constructed from two army trench periscopes. The etalon plates, separated by the spacer, are interposed between the collimator and the telescope which are adjusted for parallel light. Instead of a slit at the end of the collimator there is a small square opening. Multiple images of this opening will be seen if the plates are not parallel. The spacer is ground until the images superimpose; then the interference fringes should appear. By applying a slight pressure, the pins to be adjusted can be determined. For best results, the pins should be polished until the fringes are sharpest when no outside pressure is applied.

With small separations, the changing atmospheric pressure shifts the patterns excessively. Consequently for long exposures it is necessary to place the Fabry-Perot etalon in a constant pressure chamber. The aluminum chamber used in photographing λ8761 of caesium is shown in Fig. 4. The etalon was firmly mounted inside the chamber. Optically flat windows were placed on both ends of the chamber and tilted slightly to throw the reflection ghosts off the pattern. A sensitive barometer was used as a pressure gauge to show any possible change in the

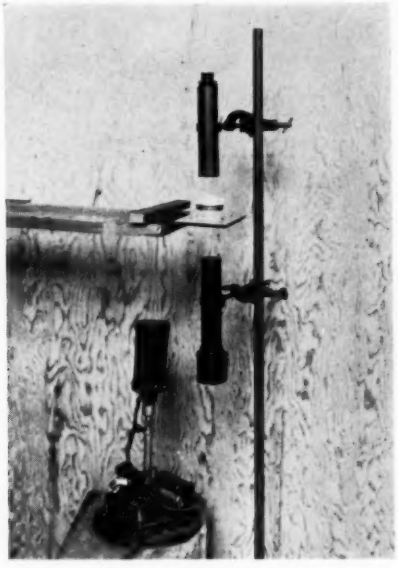

FIG. 3. Apparatus for testing spacers.

FIG. 4. Pressure chamber.

internal pressure due to improper sealing. The etalon was adjusted for parallelism by removing three screw plugs in the end of the pressure chamber; a special hook-wrench being used to adjust the etalon fingers. The screws were then replaced and sealed with glyptol.

The dispersion instrument in use is a 60-degree glass prism of index 1.75, which rests on a turntable for ease in obtaining the minimum angle of deviation. The camera is mounted on

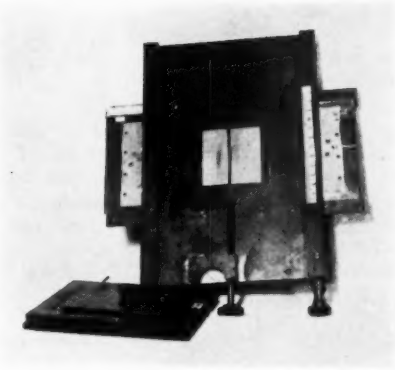

FIG. 5. Plateholder.

the same vertical axis as the prism and can be easily rotated from red to blue.

It is often convenient to change cameras either for check measurements, or to accommodate various intensities or dispersions. The camera holders were made so that the exchange could be made simply by loosening two screws. Four cameras have been found sufficient thus far: their focal lengths are 30, 50, 76 and 100 cm. They consist of 6.5-cm diameter aluminum tubes with a lens mounting at the prism end and a plateholder at the opposite end. It is often desirable to take intensity measurements; hence a special plateholder has been designed as shown in Fig. 5. The plate can be shifted vertically or horizontally and the width of the camera slit can be varied.

The etalon plates are silvered by the evaporation of silver in a vacuum. It has been found advisable to resilver about once a month to insure good surfaces at all times.

While this instrument has so far only been used with the etalon in the infrared and visible, it can be used in the ultraviolet with either the etalon or Lummer plate by replacing the glass optical system with one of quartz.

A Recording Physical Densitometer*

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(Received April 17, 1936)

The principal schemes of photoelectric control which may be applied in the design of a recording physical densitometer are: (1) The direct reading method in which the response of the cell to the light passed by the density is used to move the recording stylus. (2) The constant response method in which the cell indicates the attainment of a predetermined intensity level for the light passed consecutively through the density and a light-modulating system to which the recording stylus is linked. (3a) The intensity matching method in which equality of intensity between two beams, one passing through the density and the other passing through a light-modulating system, is indicated by a single cell exposed alternately to the two beams. (3b) An intensity matching system like (3a) in which equality of intensity of the two beams is indicated by equality of response of two cells one in each beam. The merits and shortcomings of each method are discussed and upon the basis of this discussion the last method (3b) is selected as most nearly fulfilling the specifications of an instrument for the sensitometric department of the Eastman Kodak Company Laboratories. Details of the design of this recording densitometer are explained at some length. The chief items of interest are the beam-splitter, the light-modulator, and the photoelectric control system. A discussion of the performance of this instrument and the variables which influence the performance concludes the paper.

THE testing of photographic materials by methods of routine sensitometry necessitates the reading and plotting of a great many densitometric data. Fifteen or twenty determinations of density are usually involved in obtaining the characteristic curve of a single sample. Several dozen characteristic curves may be required to get complete information on a single emulsion. When these measurements are made by visual photometric matching, the work is necessarily slow, and, unless the observer is relieved at frequent intervals, it may become fatiguing and hence inaccurate.

A physical densitometer, if it can better the speed and rival the accuracy of the routine visual method, has a definite place in the photographic laboratory. There is little doubt but that a recording photoelectric instrument can be made to work faster than the human observer and recorder, but the question of relative accuracy needs careful consideration and the final proof must be a workable, practical instrument.

The first part of this paper is devoted to a discussion of several methods of photoelectric control available to those interested in the design of a densitometer. An analysis is made of the shortcomings and advantages of each system from the points of view of accuracy, ruggedness, and speed. The second part gives a description of an instrument which was designed and built for the sensitometry department of these laboratories.

* Communication No. 587.

THE ALTERNATIVE METHODS OF RECORDING STYLUS CONTROL

To be of the greatest usefulness, a recording densitometer should plot equal increments of density ($\log_{10}$ of the reciprocal of optical transparency) as equally spaced ordinate values. This point is mentioned because several devices have been described as recording densitometers which are in reality recording transmittance meters. There are several methods by means of which photoelectric response to light transmitted by the material may be made to control a stylus so as to indicate density upon the paper. Since the optical and mechanical design of any recording densitometer is entirely dependent upon the control means adopted, it is of interest to list the possibilities:

1. A method in which the response of the cell* is used directly to control the position of the recording stylus. In an instrument built upon this plan, it may be supposed that the intensity of the light incident upon the photographic deposit is constant. The cell measures the transmitted light which, of course, varies as the trans-

* The word "cell" is intended here and in the following as a general term to include all radiation-responsive devices. None of these devices, i.e., thermopile, bolometers, photovoltaic, photoconductive, photoemissive or barrier type cells, should be excluded from this general discussion, nor, indeed, from practical consideration, until proven inapplicable.

parency of the sample. The response of the cell to illumination may be linear or it may bear some other functional relationship to the illumination. The cell response must be utilized to cause a movement of the recording stylus which is logarithmically related to the reciprocal of the measured illumination.

2. A method in which the cell response is used to indicate the attainment of a previously determined intensity level. For this purpose, it is required that the light, either before or after passing through the photographic deposit, shall be modulated. The modulating means must be linked, mechanically or electrically, with the density recording stylus, and the setting at the moment when the standard intensity is attained will be the measure of density.

3. Methods in which the cell response is used to indicate equality between the illumination furnished by a comparison beam and by the beam passing through the density. One of the beams must be modulated in intensity and the setting of the light-modulating means may be used, as in the second method, to indicate the value of density.

There are two modifications of this plan: (a) A single cell is used to receive the two beams alternately and constancy of cell output indicates equality. (b) Two cells are used, one in each beam. Their potentials are opposed and zero current results when equality is attained.

It is unwise to make any general statement as to which of the four possibilities is the best. Examples might be cited of the successful use of each in measuring densitometers and it is conceivable that any of them might be applied to an automatic recording instrument. A brief discussion of the virtues and shortcomings of each will be of interest.

The first method, i.e., the direct-reading plan, requires stability of the light source and the cell during the measurement. Then too, there may be some difficulty in applying the illumination-response characteristics of the cell to a stylus movement which is linear with density.

By installation of somewhat expensive equipment, the voltage supply may be regulated to within 0.5 percent, thereby holding the light source intensity to within one or two percent. Recalibration of the lamp as it ages cannot be avoided. Some photo-cells can probably be depended upon for stability for the short time required for a single reading, so that, if means are provided for frequent checking of this factor, a reliable instrument might be made. The principles involved in the design of logarithmic scale indicating instruments, i.e., decibel meters, might be applied to a recording instrument. The logarithmic response achievable by the combination of a linear response photoemissive cell in the grid circuit of the triode tube might simplify construction according to the direct-reading method. Such a circuit, in which the plate current of a triode tube can be made logarithmically proportional to the illumination measured by a photo-cell, has been described by Hardy.[1]

On the whole, it is the author's opinion that at present, the direct-control method is not the best choice, if a high degree of accuracy is required, if the density range to be read exceeds 0 to 1.0, if the instrument is to be used by untrained operators, or if frequent recalibration is to be avoided. It should be borne in mind, however, that improvements in the stability and sensitivity of photoelectric cells, amplifying equipment, and voltage stabilizing equipment may alter this situation. The simplicity of the direct-reading method is a strong point in its favor.

The second method, i.e., the constant intensity plan, also requires stability in both light source and cell, and so is open to the objections which have just been rehearsed. Should it be possible to overcome these difficulties, an elegant design of the instrument and its associated control circuit is possible.

The instrument would require a single optical path with a light-modulating means between the lamp and density. A photoemissive cell could be used to measure the transmitted light. An amplifier associated with the cell could be so designed that a very small departure in cell output from a predetermined critical value would cause a large change in the amplified output.* These large changes could be used, for example, through the medium of a magnetic relay, to determine the sign of the light modulation so as to maintain the illumination of the cell at the critical value.

Method 3 (a) puts no requirement upon the stability of either light source or photoelectric circuit. If both cells have the same spectral response, method 3 (b) allows instability of the source but requires that the two cells shall either

[1] Arthur C. Hardy, "A Recording Photoelectric Color Analyzer," J. Opt. Soc. Am. **18**, 106 (1929).

* This is a characteristic of several of the automatic volume control circuits used in radio reception. In these, a small change in signal strength produces a large change in the gain.

be stable or shall be possessed of instability in the same amount and character.

The single-cell flicker method is theoretically the soundest of all. It introduces, however, some mechanical and optical difficulties which are avoided by the double-cell comparison method. The double-cell method also possesses another possible advantage in a diffuse-reading densitometer. The electro-optical efficiency, determined on the basis of the power output of the measuring cell, is higher than is obtainable in a flicker densitometer.

An explanation of this last statement requires a brief discussion of the optics of density measurement. To measure density diffusely necessitates either that the light incident upon the sample shall be diffuse or that all of the transmitted light shall be collected by the measuring element. This subject has been treated by the author in a series of papers.[2, 3, 4] In the single-cell (flicker system) densitometer, the photo-cell surface must be removed from the density a distance of two inches or more to allow space for the entrance of the comparison beam. Obviously, all of the light transmitted by a scattering medium such as the photographic deposit, cannot be collected under these circumstances. The alternative is to diffuse the incident light with a consequent loss of optical efficiency.

With the double-cell system, if a cell of the barrier type* is used without any covering glass, the flat photosensitive surface can be placed so close to the density that practically all the transmitted light can be collected. Without any diffusing material in the system, true diffuse density values are obtained.[4]

The power output of a cell in the single-cell system should be compared with that of a cell in the double-cell system under circumstances which provide the most favorable conditions for both. Such a test was made. In both cases, the most sensitive photo-cells which could be obtained were chosen. For the single-cell system, this proved to be a special caesium oxide-coated photoemissive cell. For the double-cell system, the cell had to be of the barrier type. A commercial cell believed to be a silver-selenide coating on iron was chosen. The diffusing material used with the photoemissive cell was of the highest transmission compatible with the requisite diffusion. In both cases, the external resistances were adjusted for maximum power output.

The power output (measured by the product of external resistance and current squared) was about twenty times greater for the barrier-type photo-cell in its appropriate optical system.

It seems quite possible that the simplest and most rugged automatic densitometer may result from the use of the method of measurement which has available the greatest amount of power from the measuring element. This and other practical arguments in favor of the two-cell system make it worth while to look into the seriousness of its major objectionable feature. The objection may be phrased as a question: How nearly will the opposed output of any two cells remain zero when the illumination on each is either constant or variable in the same manner? A favorable answer to this question will follow if both cells are stable or if both exhibit the same degree of instability when exposed to the same conditions.

It has been shown that considerations other than stability definitely single out the barrier-type cell for the two-cell densitometer. Fortunately, from the point of view of stability also, a circuit involving these cells seems to be promising: (1) All cells of this type appear to be comparatively free from the effects of fatigue and aging. (2) The external circuit can minimize that part of the fatigue effect which is caused by cell resistance change. (3) By requesting the manufacturer to supply "matched" cells from the same processing lot, two cells of very similar characteristics may be obtained. If closely matched cells are not easily found, it is still possible to cut a single element diametrically in two, thus producing a pair which are nearly identical.

[2] Clifton Tuttle, "The Relation between Diffuse and Specular Density," J. Opt. Soc. Am. **12**, 559–65 (1926).

[3] Clifton Tuttle, "Densitometry and Photographic Printing: Illumination of the Negative and Its Effect upon Density," J. Opt. Soc. Am. **24**, 272–78 (1934).

[4] Clifton Tuttle and B. C. Hiatt, "A Note on the Measurement of Photographic Densities with a Barrier-Type Photocell," J. Soc. Mot. Pict. Eng. **26**, 195–203 (1936).

* Similar advantages in efficiency of light collection may be claimed for other radiation-sensitive elements, i.e., the thermopile and selenium cell. These are omitted from the present consideration—the first, because of slowness and insensitivity, the second, because of instability.

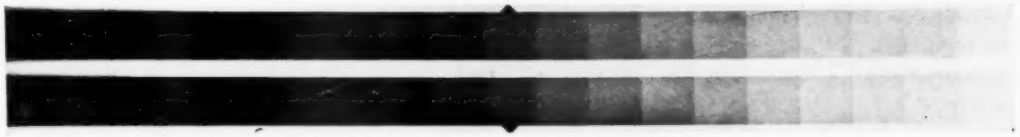

FIG. 1. Sensitometric strip from Eastman IIb sensitometer.

It should be possible to set up an opposed potential circuit of almost any desired stability by careful matching of sensitivities, internal resistance, fatigue rate, and spectral response characteristics of two cells. Ordinarily in densitometers, however, the ultimate refinements of matching are probably not necessary. As a practical test, two stock Weston Photronic cells were connected with opposed potentials in parallel with a galvanometer. The circuit was balanced by adjusting the distance of one cell from the light source which illuminated both. The galvanometer sensitivity was such that a variation of intensity of one-tenth of one percent on one of the cells was detectable. During the week for which the set-up was left undisturbed, no variation was observed. Changes in line voltage and consequent color temperature variation of the source caused no readable variation.

DESCRIPTION OF THE LABORATORY RECORDING INSTRUMENT

The instrument which will be described has been designed expressly to fit into the routine procedure of the sensitometric department of these laboratories. The general specification given to its designer was that it should do the routine work as accurately and as rapidly as a photometrician. Specifically, this general specification may be framed as a list of concrete items:

1. It must read and plot the results from the IIb sensitometer strips.[5] (See Fig. 1.)
2. A single strip must be read and plotted in four minutes or less. (In routine visual work, two people changing off—one reading while the other records—will work at the rate of thirty strips per hour or one strip per person in four minutes.)
3. A density range of 0.0 to 3.0 (1 to 1000 in intensity of transmitted light) must be covered.
4. The error should not exceed the photometric error (about ±0.01 density).
5. It must read diffuse density.
6. It must be mechanically rugged—free from the need of adjustment or easily adjusted by operators unskilled in electronic circuits.
7. Certain obvious cost limitations must be observed to justify the instrument on economic grounds.

Upon the basis of these specifications, it is possible to discard two of the control methods cited in the first part of the paper. Methods (1) and (2), which require constancy of two factors, *viz.*, control circuit sensitivity and light source output, do not inspire confidence. Preliminary experiments have been tried with two of the control systems suggested previously, i.e., the photo-cell cathode to grid circuit, which gives logarithmic plate current, and the critical current tripping circuit. Either can be made to operate successfully, but to maintain an accuracy of 0.01 in density requires repeated adjustment. These adjustments seem to need the services of one thoroughly familiar with electronic circuits in general and with all the probable causes of error.

The remaining choices are the two matching methods, (3a) and (3b). The second, the double-cell system, has been selected because it seemed the simplest way of fulfilling the specifications, especially that of ruggedness.

There are numerous possible mechanisms which might be devised to operate a recording densitometer when the two-cell control system is used. Some of the elements in the design of this particular instrument which seem to be of the greatest novelty will be described in detail, but the general principles of its operation may be passed over rather quickly. It is hoped that the schematic drawing (Fig. 2) and the photograph (Fig. 3) will help to elucidate the following description.

Light from a source is divided into two parts. One part illuminates the comparison cell and

[5] L. A. Jones, "A Motion Picture Laboratory Densitometer," J. Soc. Mot. Pict. Eng. **17**, 536–58 (1931).

the intensity of this illumination may be manually regulated within a small range to set the instrument zero by balancing the output from the two cells. Light in the second beam traverses an aperture variable in area over a maximum to minimum ratio of 1000 to 1.0. In the drawing (Fig. 3), the two beams are shown as if they originated from different sides of the lamp. The actual optical system which will be described later makes use of a beam-splitter. After passing through the variable aperture, the light is incident upon one of the areas of the sensitometric strip. Nearly in contact with the photographic material is placed the surface of the measuring photo-cell. The two photo-cells, the one in the comparison beam and the other in the measuring beam, are connected with opposed potential to a galvanometer. The combined output of the two cells when illuminated to the same level is zero.

Light provided by a second source and collimated by a second optical system is reflected by the galvanometer mirror upon a large condenser lens. The lens, except for an open slit at the zero position of the galvanometer, is covered by an opaque mask. At zero galvanometer deflection, the light is concentrated upon a third photocell. The output of this cell is used to close a relay which initiates the operation of recording and of shifting the coordinate paper and sensitometric strip. Characteristics of the galvanometer and the relay are dealt with in the following pages.

In operation, the first step of the sensitometric strip is registered over the window of the measuring photo-cell, thereby decreasing the intensity on this cell and throwing the photocell-galvanometer circuit out of balance. A hand-operated switch closes the circuit of a magnetic clutch, which drives the diaphragm-changing mechanism in the direction which increases the light in the measuring beam.

When the intensity on the measuring cell has become equal to that on the comparison cell, the galvanometer deflection is reduced to zero and the relay is tripped. The relay circuit energizes a solenoid pulling a plunger which releases an over-running clutch, allowing it to make one revolution. The over-running clutch drives a shaft upon which are cams which operate two switches. The first small fraction of the turn of the shaft through the medium of these switches de-energizes the diaphragm-driving clutch and discharges a spark through the graph paper from a metal pointer. The pointer is

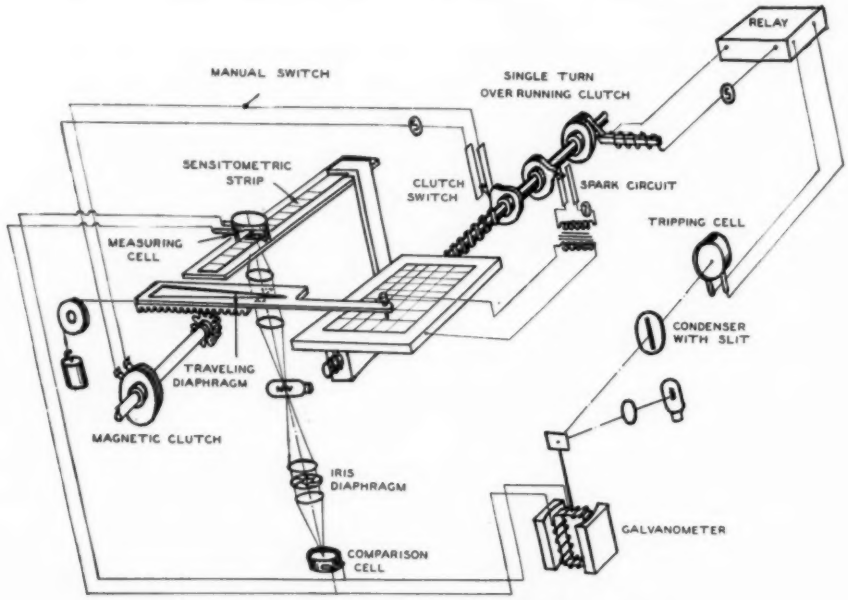

FIG. 2. Schematic diagram of automatic densitometer.

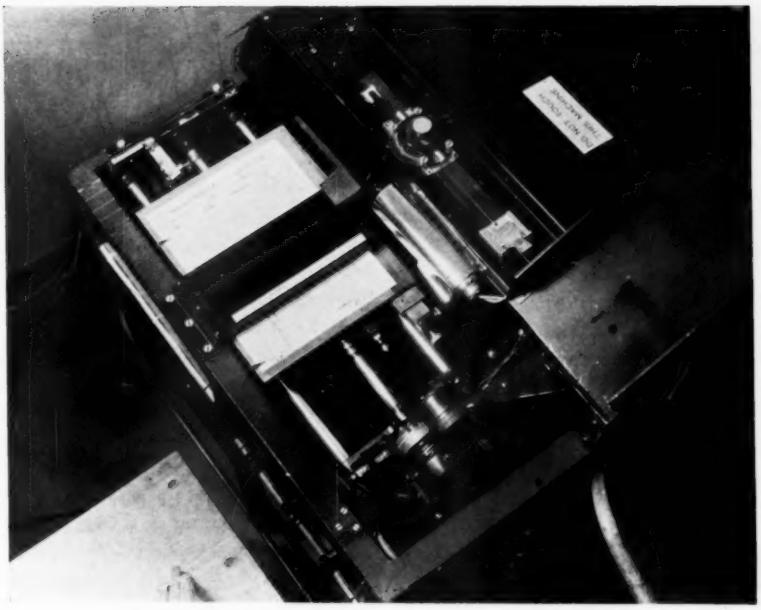

FIG. 3. Top view of densitometer.

attached to the end of the traveling diaphragm; thus, its position at all times is a positive indication of the disclosed area of the variable aperture. At the time of the spark discharge, the sum of the effective density of the diaphragm in its optical system and the density of the material being measured is *constant*. The functioning of the diaphragm is described more fully in the succeeding pages.

Upon the shaft which is rotated by the overrunning clutch is cut a screw the lead of which is equal to the 0.15 increment on the abscissa scale of the graph paper. As the shaft completes its single revolution, a stainless steel carriage table, upon which the graph paper is first manually registered and then held by suction, is moved forward the proper amount. Attached to the table is an arm which pulls the sensitometric strip the distance of one step. Special coordinate paper, in which the divisions are of the proper size with respect to the steps of the sensitometric strip, must be used.

At the termination of the operations just described, the instrument has set itself for the recording of the second point. The diaphragm has been pulled backward enough to unbalance the photoelectric circuit even if the second step should be no greater in density than the first. The magnetic clutch which drives the diaphragm is energized as soon as the shaft has completed its revolution and the upward travel of the diaphragm continues until a match of the two cell intensities is again achieved. Upon the completion of the point-by-point record of all twenty-one steps, the driving circuit is automatically broken and the paper may be removed.

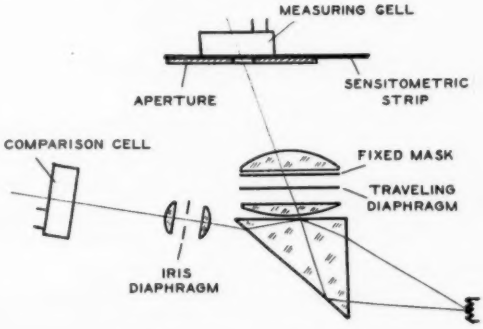

FIG. 4. Measuring optical system.

For the most part, the instrument makes use of conventional mechanical and optical systems which need no further explanation. A discussion of the few matters which the author believes to be new or of special interest follows.

The Optical System

The beam-splitter

In any matching photometer, the light in both beams should originate from the same lamp filament area and should pass through identical optical systems. For the purpose of dividing the beams, use is frequently made of a beam-splitter consisting of two right-angle prisms cemented together at their hypotenuse faces with a thin sputtered or evaporated metallic plating on one of the cemented surfaces. All such beam-splitters are slightly selective and usually unstable if they are required to reflect and transmit much light. The beam-splitter used in this instrument is very simple and seems to avoid some of the difficulties of the conventional type. It makes use of an unsilvered right-angle prism. The light source is slightly decentered with respect to the prism axis as shown in Fig. 4. The totally reflected light serves to illuminate the entire horizontal surface of the prism uniformly because of the decentering.

Light reflected at the top surface and incident on the hypotenuse surface at angles less than the critical angle is refracted through the surface. Light traversing the prism in the vertical direction is rendered parallel by a plano-convex lens and brought to a focus in the plane of the measuring photo-cell (a filament image) by a second plano-convex lens. Light which passes through the prism in the nearly horizontal direction is received by a similar double lens and brought to a focus on the comparison photo-cell.

The variable aperture

Between the lenses in the vertical beam is placed the variable aperture which is capable of changing the intensity of the image on the photographic material and measuring cell by a factor of 1000. It is required that the position of the aperture-varying means shall be a measure of density. It is conceivable that this end could be accomplished with a conventional iris diaphragm and the proper mechanical linkage to convert the rotational movement to a linear movement of the stylus logarithmically proportional to the inverse of the opened area. Fragility and backlash and the fact that the coupling mechanism required to convert the movement is complicated are serious drawbacks to this idea. It is also conceivable that an optical absorbing wedge might be used. The worst objection is impermanence. Gelatin wedges, colloidal deposit wedges, and evaporated metallic wedges all suffer from this defect.

The combination of a shaped movable diaphragm and fixed mask (Fig. 5) devised for this densitometer is believed to be both permanent and rugged. The mask is located permanently between the plano-convex lenses. The movable diaphragm is mounted on a cart with ball-bearing wheels and it slides over the fixed mask with a clearance of about 1/16 inch. It has been cut in a brass plate from a calculated curve and the shape has been slightly altered by trial-and-error testing in the finished instrument. The gradient (first derivative of area and distance) is such that a movement of 0.81 inch will double the intensity transmitted by the aperture to the photographic material. The recording stylus, which is a sparking point, is attached to the end of the cart which carries the diaphragm. Obviously, there is no chance for lost motion between the intensity-modulating means and the recording means.

In Fig. 6 is shown a series of pictures of the openings uncovered by the traveling diaphragm. The smallest area is about 1 mm square and is located on the optical axis of the measuring system. The smallest dimensions of both diaphragms are great enough to avoid errors caused by diffraction or by the accidental accumulation of dust. The original shaping of these smaller

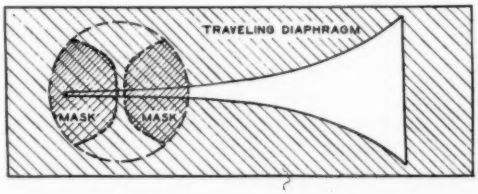

Fig. 5. Diaphragm and mask.

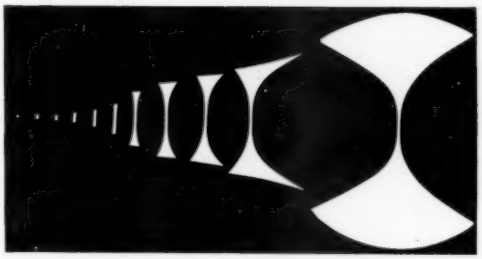

FIG. 6. Series of disclosed apertures.

portions, however, must be very carefully done as an error of 0.0005 inch will cause a density error of about 0.01.

GALVANOMETER AND CELL CIRCUIT

Sensitivity

It is obvious that the measuring cell circuit in this instrument operates always at the intensity which is transmitted by the aperture set at the minimum area—or rather the area corresponding to zero density. When any density up to 3.0 is interposed in the system, the light passed by the diaphragm is increased until the intensity received by the measuring cell is equal to the zero density-minimum area value. The important value concerning the cell sensitivity, then, is the current corresponding to the minimum diaphragm setting. It was found that, with various commercially available cells, connected in opposed potential circuits, currents from 2.0 to 6.0 microamperes could be obtained through 500 ohms external resistance when the comparison cell was darkened. The demanded accuracy of 0.01 in density corresponds to about two percent in intensity variation. It happens, then, that a cell current variation of 0.04 microampere with the least sensitive cell or 0.12 microampere with the most sensitive cell must be able to deflect the galvanometer sufficiently to operate a relay capable of initiating the necessary mechanical movements.

There is no difficulty whatever in constructing a photoelectric relay which will operate positively, on and off, with a galvanometer spot movement of 1 mm. The galvanometer throw can conveniently be made about 1 meter without adding to the bulk of the densitometer. The sensitivity specification of the galvanometer then is 0.04 microampere per millimeter.

Galvanometer period and instrument speed

It is evident that, for practical reasons, the galvanometer period should be as short as possible. This request was made to the Leeds and Northrup Company together with the other specifications of the instrument. This company produced a "narrow coil" galvanometer with a sensitivity of 0.03 microampere per millimeter, and a period of 0.5 second. The coil carried a plane mirror 5 mm in diameter.

The galvanometer period is, to a large extent, the governing factor for the speed of the diaphragm movement. If the lag of the galvanometer movement with respect to the cell current change is constant, the effect is to alter the zero setting of the densitometer and simultaneously to shorten the usable density range. If the lag is small, so that the spurious density value differs by a small amount, say 0.01, from the true value, the consequences are not serious, even if the error is not constant throughout the density range. The author asked Dr. L. Silberstein to analyze the problem from the standpoint of the dynamics of the galvanometer and the speed of the diaphragm. He finds that, for the density error not to exceed 0.01, a critically damped or slightly underdamped galvanometer must have a period not greater than one-fifteenth the time required for the diaphragm to travel at uniform velocity from 0 to 3.0.

With the Leeds and Northrup galvanometer, this would put the velocity of the diaphragm at about 0.4 (density units) per second. The characteristic curve which would take the longest time in plotting would be one in which all twenty-one steps were required for density to increase to 3.0. The average diaphragm travel per point in plotting such a curve would be about 1.5 units, which would consume four seconds per point, making the reading time for the entire curve eighty-odd seconds. When to this time is added the sum of intervals between points used to advance the strip and paper, it is possible that the speed of the instrument would be rather disappointing. Fortunately, because of the fact that characteristic curves in the region of interest in routine testing always have a positive gradient,

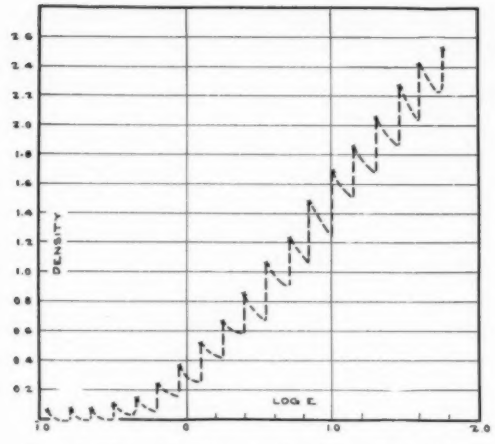

FIG. 7. Characteristic curve showing path of stylus.

it is entirely feasible to prevent the return of the diaphragm to zero after each point is made. It is quite satisfactory for the diaphragm to travel upward with a sort of ratchet movement. In rare cases, however, an area might be so seriously scratched that its density would be less than that of its predecessor. For this reason, it is safer to drop the diaphragm backward slightly after the recording of each point. The pull-back can occur while the paper carriage and sensitometric strip are being transported.

To accomplish the pull-back, the diaphragm carriage has been attached by a cord running over a pulley to a weight which falls in a cylinder closed at the lower end by a valve. The weight acts as a piston against an air cushion and the distance of fall can be controlled by the size of the valve opening. The path of the diaphragm stylus in plotting points is shown by the dotted line in Fig. 7. The average time for recording of a point is about one second.

THE RELAY

The function of the relay is to turn on and off 75 watts of power required for the clutch-controlling solenoid. It should do this job without lag at the instant when the galvanometer deflection is reduced to zero. It should function at the same point regardless of line voltage fluctuation even though the fluctuation is great enough to cause a 50 percent change in light flux from the galvanometer lamp.

First thought on this problem favored the thyratron tube as a control device. A relay, using a gas-filled caesium cell as the light-sensitive element, a grid glow tube as an amplifier for the photoelectric current, and a thyratron to supply the power when triggered off by the grid glow tube, was built and used for several months with only fair success.

During this period it required frequent adjustment as the tube characteristics changed, and it was not independent of line voltage. A five-minute heating period was required for the thyratron cathode. Following this preliminary wait, there was a period of about twenty minutes of instability until temperature equilibrium was established. These delays tended to lessen the usefulness of the instrument.

The relay which is on the densitometer at present is rugged, accurate, instant-starting, and never needs adjustment. It uses a barrier-type cell to receive the galvanometer beam, and the cell output is sufficient to operate a mechanical relay. For this latter purpose, the Weston "Sensitrol" is used. The Sensitrol is a contact-making galvanometer which is rated for a fairly high secondary current (200 ma at 6 volts d.c.). It will close positively with a primary current of a few microamperes because the feeble actuating current serves to swing a fairly heavy contact arm into the field of a permanent magnet. The pointer must be reset mechanically by pulling the contact point away from the permanent magnet.

The greatest objections to the Sensitrol for use in the densitometer were its sluggishness caused by the high inertia of its pointer and its tendency to overswing and oscillate when it was mechanically reset. These defects have been overcome in an unconventional manner: An additional permanent magnet is placed outside of the case with its field at right angles to the field of the contact point magnet (Fig. 8). As this magnet is shifted, the pointer follows, and the tripping sensitivity can be increased to any degree desired. The period is decreased and the pointer does not oscillate when reset. The action of the relay may be compared to that of a toggle joint. Since the cell illuminated by the galvanometer beam will deliver about fifty times as much current as is required to trip the relay, it

FIG. 8. Sensitrol relay and added magnet.

is almost independent of variations in lamp intensity or cell sensitivity.

PERFORMANCE CHARACTERISTICS

The automatic densitometer, at the time this is written, has been in service in the sensitometric department of these laboratories for six months. During this time, occasional changes and adjustments have been necessary, but for the past two months, since the installation of the electromagnetic relay just described, the instrument has run without attention other than lubrication of moving parts. Its accuracy is not influenced by the line voltage fluctuations of 15 percent.

The greatest part of the work handled by the densitometer is the plotting of families of curves resulting from four different development times of motion picture positive emulsions.

The results of a time study of the recording operation may be of interest. The values given are for the recording of a complete set of data for a sensitometric strip:

	SECONDS
Registering one sheet of coordinate paper	10
Registering sensitometric strips (8 times)	40
Reading time (8 curves)	280
Other operations (resetting paper carriage, etc.)	70
Total time for 8 strips	400
Time per strip	50

The time of 50 seconds per strip is considerably less than the requirement set forth in the specifications, but it is worth while, nevertheless, to consider what improvements might be made in this speed.

About 25 percent of the time is used up by necessary manual operations. There is little hope of decreasing this time except by increased manual dexterity, or better by automatic feeding of graph paper and strips from rolls. The time used in the mechanical operations of shifting the paper accounts for about 20 percent. The speed of this operation cannot be materially increased as long as an intermittent movement of such large masses is required. It is conceivable that the remaining 45 percent of the time, i.e., the period during which the diaphragm is moving upward, could be decreased if the sensitivity of the measuring cell could be increased or if more light could be used. Either variation would allow higher torque and consequently a shorter period for the galvanometer.

Although the instrument ever since its completion has been kept busy on routine work, some time has been available to investigate the effect upon performance of some variations in set-up and use.

Lamps of various types and wattages have been tried. Sources of 200, 300, 400, and 500 watts rating may be used interchangeably without disturbing the calibration. The heat from the 400- and 500-watt lamps is great enough to cause a perceptible temperature difference between the cells and a slow drift of the zero setting. This effect could be overcome by forced air-cooling of the cells or by rearranging the optical system so that both are exposed to more nearly identical temperatures. However, since the lower wattage lamps do not cause any such trouble and are preferable for other reasons, it is not necessary to apply either remedy.

Lamps with biplane filaments, monoplane filaments, or floodlight-type case filaments all give the same results and the effect of changing from a spherical to a cylindrical bulb is not detectable. At present, a 300-watt monoplane filament lamp operated at about 15 percent below its rated voltage is used in the instrument.

Careful matching of the photo-cells, at first thought to be essential, has proved to be unimportant. Stock commercial elements sold under the names of "Photronic cells," "Electro-

cells," and "Photox cells" have been used with equal success so far as stability is concerned. Two Photox cells are at present used in the instrument. They are particularly suitable because their unfiltered spectral response closely matches that of the eye. With these cells, readings of materials coated on various colored supports are identical with those obtained with the laboratory standard visual densitometer.

When heavy paper stock (2 lbs./1000 17 by 22-inch sheets) is used, the nonuniformity of dielectric strength gives rise to a slight difficulty. With such stock there is an occasional error of 0.02 inch in registration of the spark. This is equivalent to a density error of ± 0.01. With thinner stock, (13 lbs./1000 sheets), the error arising from this cause is negligible. Scratches or dirt on the measured areas are, of course a source of error which must be recognized, but since all sensitometric tests are machine-processed and are handled with the greatest care, dirty or abraded areas are rare.

An interesting comparison of results of routine visual densitometry with those of the automatic instrument may be seen in Table I. A single sensitometric strip on positive film was read with both instruments on four consecutive days. The data obtained in each case are given for each case together with the computed averages and maximum errors. This and all the similar tests, which are run periodically, show a slight preference in favor of the repeatability with the automatic instrument.

TABLE I. *Comparison of visual and automatic densitometer results.*

STEP	READINGS ON FOUR DAYS					AVERAGE	MAXIMUM ERROR
	Automatic Densitometer						
1	2.46	2.45	2.47	2.45	2.47	2.46	0.01
2	2.30	2.30	2.31	2.29	2.31	2.30	0.01
3	2.03	2.03	2.04	2.03	2.03	2.03	0.01
4	1.80	1.80	1.80	1.79	1.80	1.80	0.01
5	1.58	1.57	1.58	1.56	1.57	1.57	0.01
6	1.30	1.30	1.31	1.31	1.30	1.30	0.01
7	1.10	1.09	1.09	1.09	1.09	1.09	0.01
8	0.88	0.88	0.88	0.87	0.88	0.88	0.01
9	.68	.68	.68	.67	.68	.68	0.01
10	.50	.50	.50	.50	.50	.50	0.00
11	.34	.34	.34	.34	.34	.34	0.00
12	.22	.22	.22	.21	.22	.22	0.01
13	.14	.14	.13	.13	.13	.13	0.01
14	.09	.09	.09	.09	.09	.09	0.00
	Visual Densitometer						
1	2.44	2.46	2.42	2.46		2.45	0.03
2	2.25	2.27	2.27	2.27		2.27	0.02
3	2.00	2.03	2.00	2.04		2.02	0.02
4	1.80	1.78	1.79	1.79		1.79	0.01
5	1.55	1.55	1.54	1.55		1.55	0.01
6	1.30	1.31	1.29	1.27		1.29	0.02
7	1.09	1.09	1.09	1.08		1.09	0.01
8	0.88	0.88	0.87	0.88		0.88	0.01
9	.69	.70	.68	.67		.69	0.02
10	.49	.51	.49	.48		.49	0.02
11	.34	.34	.34	.33		.34	0.01
12	.21	.22	.22	.22		.22	0.01
13	.14	.15	.14	.14		.14	0.01
14	.08	.08	.09	.08		.08	0.01

The Selection of Color Temperature Altering Filters

ROGER S. ESTEY, *Electrical Testing Laboratories, N. Y.*

(Received May 5, 1936)

GENERAL PRINCIPLES

COLOR temperature altering filters have their greatest use in the actual measurement of color temperature and in the photometry of incandescent lamps. For these purposes it is important that the filters have such a character of absorption that a beam of incident light which has a black body distribution is converted to a new distribution which is still Planckian in character. By appropriate filter design the color of the transmitted light can be made a close match to some new color temperature color, but the exact conversion of energy from one Planckian distribution to another cannot be carried out as accurately.

The ordinary color temperature scale is inconvenient because the interval by which the filter alters color temperature depends both on the filter and on the color temperature of the incident light. However, on a scale of reciprocal color temperature the color temperature altering interval or rating is a characteristic of the filter alone. Thus in cases where the coloring matter is uniformly dispersed throughout the thickness of the material the filters can be rated in terms of their color temperature altering power per unit of filter thickness. The advantages of expressing color temperatures and color temperature intervals on a reciprocal scale using the micro-reciprocal degree as a unit were suggested by Priest.[1] (For convenience the unit might be abbreviated to the expression "mired.")

The closeness with which the color of the filtered light matches a Planckian color can be easily determined by computing the trilinear coordinates of the filtered light and comparing the plotted position of this stimulus with the locus of black-body stimuli.[2] When the color of the transmitted light lies exactly on the Planckian locus, the color temperature can easily be read off from a large scale graph on which is plotted the the trilinear coordinate "x" of points on the locus and either the color temperature or the reciprocal color temperature as may be most convenient. Such a curve is shown in Fig. 1. Colors more or less off of the Planckian locus can be assigned the nearest representative color temperature by means of a graph of isotemperature lines prepared by Judd.[3]

It is not enough that the filtered light be a good color match to some black-body color, but it is also very desirable that the energy distribution correspond as well. For example, in the photometry of heterochromatic light sources the photometric fields may have a disturbing non-uniformity of color due in large measure to serious differences in the energy distribution of the two light sources even though they are brought to nearly the same subjective color by the use of filters. Cut and try methods must be used to design filters producing a good energy match but the closeness of the fit of a given filter to the ideal distribution can be shown by plotting the logarithm of the transmission against the reciprocal of the wave-length.[4] If the filter correctly converts one Planckian energy distribution to another the curve will be linear. If a straight line is drawn which best represents the data then the color temperature altering interval of the filter is given by the expression

$$\Delta(1/\theta) = 160.7 \quad \Delta \log T/(\Delta(1/\lambda)),$$

where $\Delta(1/\theta)$ is the color temperature difference (in mireds) produced by the filter and $\Delta \log T/(\Delta(1/\lambda)$ is the slope of the best straight line through the spectrophotometric data plotted

[1] I. G. Priest, "A Proposed Scale for Use in Specifying the Chromaticity of Incandescent Illuminants and Various Phases of Daylight," J. O. S. A. **23**, 41 (1933).

[2] Deane B. Judd, "The 1931 I. C. I. Standard Observer and Coordinate System for Colorimetry," J. O. S. A. **23**, 359 (1933).

[3] Private communication. Deane B. Judd, "Estimation of Chromaticity Differences and Nearest Color Temperature on the Standard 1931 I. C. I. Colorimetric Coordinate System," J. O. S. A. **25**, 199 (1935).

[4] H. P. Gage, "Color Filters for Altering Color Temperature. Pyrometer Absorption and Daylite Glasses," J. O. S. A. **23**, 46 (1933). Although this development is based on Wein's equation the results follow for Planckian temperatures within less than half a mired for temperatures below 5000°K.

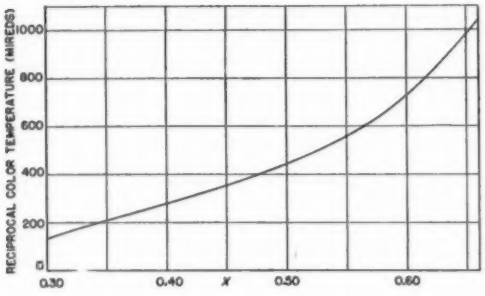

FIG. 1. Reciprocal color temperature as a function of the trilinear coordinate "x" for points on the black-body locus.

as described above. The wave-lengths are expressed in microns. This slope equation provides an approximate rating which serves as a rough check on the more laborious but more precise method of rating filters from the trilinear coordinate data.

AVAILABLE FILTERS

Certain types of color temperature altering filters are commercially available. The Wratten gelatin filters[5] include a blue and an amber series designed to alter color temperature. Their characteristics are listed in Table I.

Although these filters are not adjustable (in the sense that a glass or liquid filter can be adjusted by altering the thickness or concentration) yet in applications where the available ratings can be employed, they are exceedingly convenient.

Davis and Gibson[6] have developed an extensive group of two component liquid filters, bluish in color, one series of which has been explicitly designed to alter color temperature. These comprise filters Nos. 21 to 31 inclusive and vary in rating from 66 to 252 mireds. The color match produced by these filters is exact. The energy characteristic for two typical filters is shown in Fig. 2.

TABLE I. *Wratten photometric filters.*

FILTER No.	DESIGNED COLOR TEMPERATURE, K		RATING (mireds)	COLOR
	INCIDENT	EMERGENT		
78	2360	5500	−242	Bluish
78AA	2360	4400	−196	"
78A	2360	3200	−111	"
78B	2360	2800	− 67	"
78C	2360	2500	− 24	"
86	5500	2360	+242	Yellowish
86A	3200	2360	+111	"
86B	2700	2360	+ 53	"
86C	2500	2360	+ 24	"

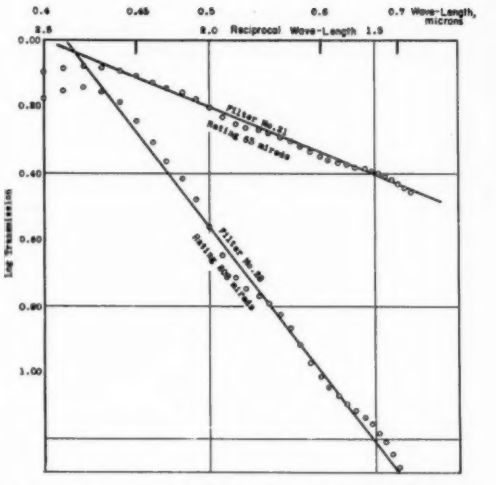

FIG. 2. Energy characteristic of two Davis and Gibson filters. The straight lines are drawn through the data at 0.5 micron using slopes computed from the trilinear coordinate data.

A color temperature raising glass filter, manufactured by the Corning Glass Works, has been described by Gage.[4] This bluish glass (Daylite, No. 590) is available in only one density which has a rating of about 35 mireds per mm.

BLUE FILTER DESIGN

If, because of various considerations such as bulk, filter thickness, inappropriate rating, etc., filters which are commercially available or which have been previously described in the literature are unsatisfactory for some particular problem, special filters can readily be designed by using colored glasses of appropriate thickness, singly or in cemented combination.

Good color temperature raising filters should have a smoothly graded increase in absorption

[5] Wratten Light Filters, 13th Ed., Revised (Eastman Kodak Co., 1934).

[6] R. Davis and K. S. Gibson, "Filters for the Reproduction of Sunlight and Daylight and the Determination of Color Temperature," Bur. Standards Misc. Pub. No. 114, January (1931).

from a high transmission in the blue to a low transmission in the red. No one coloring agent has been found which will produce this characteristic, but triple combinations of cobalt, copper and amethyst glasses can be used which are very satisfactory in converting from one Planckian energy distribution to another. The amethyst glass makes the filter transmission decrease with wave-length between 400 and 500 millimicrons. The cobalt glass has a similar effect between 500 and 650 millimicrons. Beyond 650 millimicrons the transmission of the cobalt glass rises and the copper glass is necessary to correct this increased transmission in the deep red. In applications where the best energy match is not worth the complication of a three-element design, a two-component combination can be selected to produce a perfect color match even though the energy match is less perfect. Computations indicate that two-element combinations of cobalt and amethyst glasses are more satisfactory than combinations of cobalt and copper glasses.

In designing deep blue filters samples of cobalt and amethyst glass are selected from the manufacturers' catalogs. Their colors (used with a particular light source) are plotted on the mixture diagram, singly and in combination. Cobalt and amethyst glasses plot on opposite sides of the Planckian locus and therefore a combination can be found which will lie directly on the locus. As different trial thicknesses are computed and plotted on the diagram simple interpolation will suggest the best thickness ratio. The development of a combination filter rating about 61 mireds per mm is shown on the mixture diagram, Fig. 3. The position of the blue glass (see the insert in Fig. 3) shows its color to be too green. One mm of amethyst was added but the result was found to be too purple. Intermediate thicknesses were computed and a thickness of 0.7 mm selected for the correcting glass. The complete filter consists of 2.0 mm of Corning Furnace Door Blue, No. 533 plus 0.7 mm of Bausch and Lomb Amethyst Shade B cemented together. The energy characteristic of the completed filter is shown in Fig. 4. On this and the following diagrams the straight line on the energy characteristic plot is drawn through the density at 0.5 microns with a slope computed from the trilinear coordinate data. A similar filter can be prepared using 0.5 mm of Soft-Lite No. 4 in place of the Amethyst B. Both filters have the same rating.

Blue filters of intermediate rating are obtainable by using Corning Daylite, No. 590. This

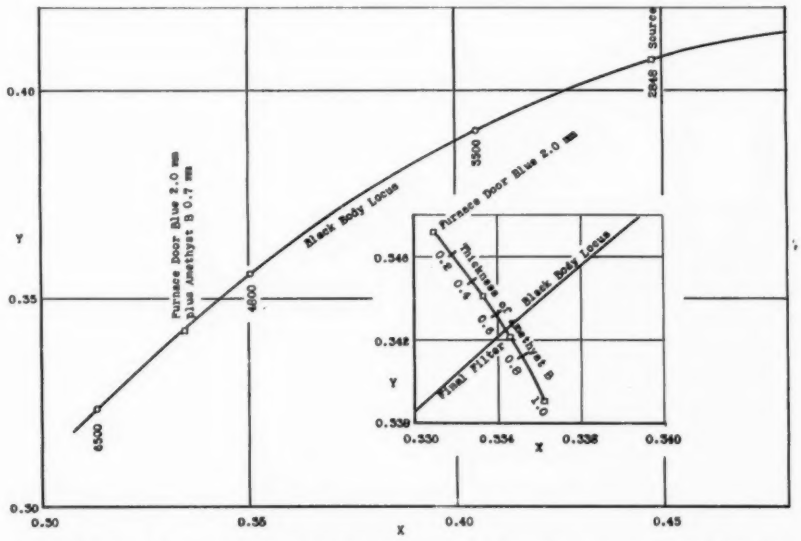

FIG. 3. Mixture diagram showing the design of a dark blue color temperature raising filter. The insert shows the effect on the color produced by adding various thicknesses of Amethyst B to 2.0 mm of Furnace Door Blue.

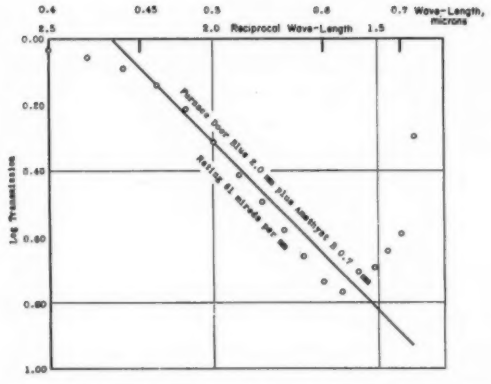

FIG. 4. Energy characteristic of the dark blue filter shown in the preceding figure. This filter has a rating of about 61 mireds per mm.

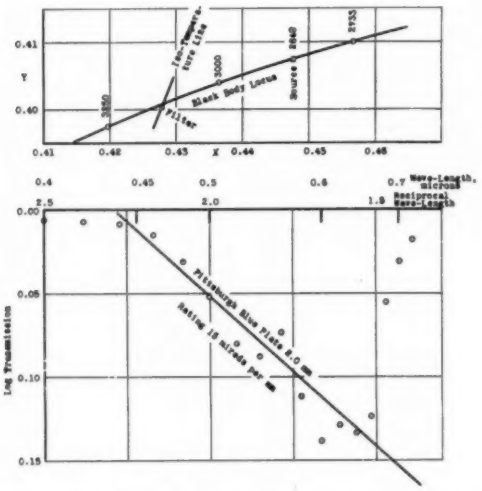

FIG. 5. Mixture diagram and energy characteristic of Pittsburgh Blue Plate. Although the color of the transmitted light is not exactly on the Planckian locus, its correlated color temperature is obtainable by plotting the appropriate isotemperature line.

glass produces a good color and energy match without further correction and is much better corrected in the red than is the filter described above. Corning Daylite rates about 35 mireds per mm.

The departure of the color of tungsten light through cobalt glass from the black body locus is so small that this material can be used for light blue filters of low rating without the need for any correction glass. Pittsburgh Blue Plate has a rating of about 15 mireds per mm and is suitable for this type of filter. The position of this glass on the mixture diagram and its energy characteristic are shown in Fig. 5. The departures from an exact color match are hardly noticeable with filters of moderate thickness.

AMBER FILTER DESIGN

Filters for lowering color temperature must smoothly increase in transmission toward the longer wave-lengths. Various amethyst glasses have the property of increasing their transmission with increasing wave-length between 500 and 700 millimicrons, but between 400 and 500 millimicrons their transmission decreases. This region can be controlled by the use of a glass of the Noviol type or an amber glass can be selected to correct the 400–500 millimicron region and to simultaneously increase the slope of the whole curve thus increasing the filter rating. For example, the combination of Corning H. R. Amber Shade C, No. 347 plus Corning Amethyst, No. 507, thickness ratio 1 : 0.70 has a rating of about 99 mireds per mm. The data on this filter are shown in Fig. 6. A filter of lower rating can

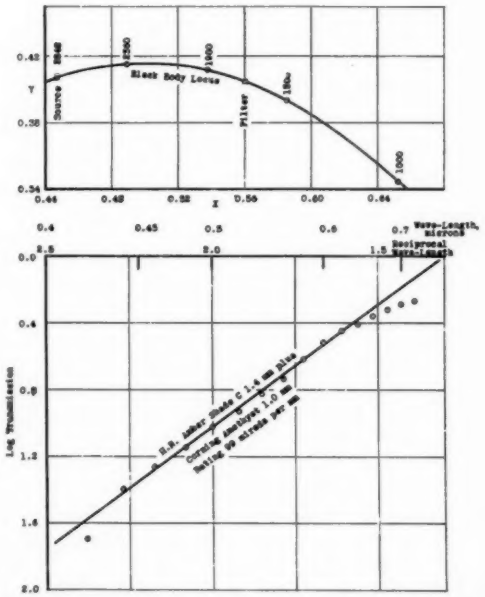

FIG. 6. Mixture diagram and energy characteristic of a dark amber filter rating about 99 mireds per mm.

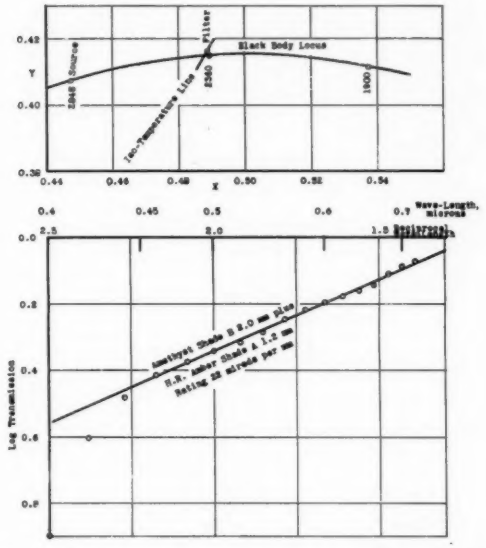

FIG. 7. Mixture diagram and energy characteristic of a medium amber filter rating about 22 mireds per mm.

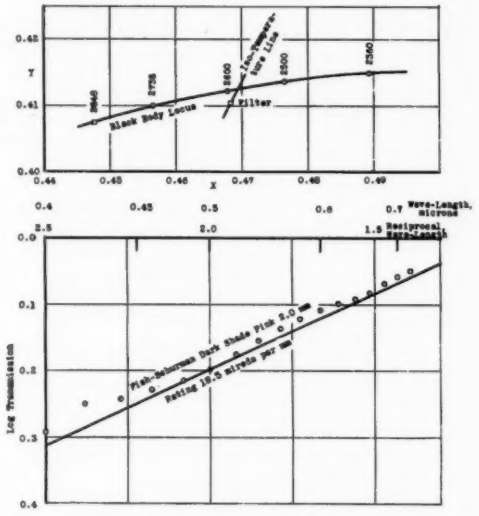

FIG. 8. Mixture diagram and energy characteristic of Fish-Schurman dark pink spectacle glass rating about 18.5 mireds per mm. The color match can be improved by a Noviol type correction glass.

be designed by combining Bausch and Lomb Amethyst Shade B with Corning H. R. Amber Shade A, No. 346, thickness ratio 1 : 0.6. This filter has a rating of about 22 mireds per mm. As can be seen from the energy characteristic, Fig. 7, the blue transmission is too low. Probably a better energy match would be obtained by substituting a Noviol for the H. R. Amber Shade A.

TABLE II. *Color temperature altering glass filters.*

FILTER COMPONENTS	C. T. INTERVAL (microreciprocal degrees per mm)
Corning Glass Works, Furnace Door Blue, No. 533 plus Bausch and Lomb Optical Co., Amethyst Shade B. Thickness ratio 1 : 0.35	61 Blue
Corning, Daylite, No. 590	35 Blue
Pittsburgh Plate Glass Co., Blue Plate	15 Blue
Corning, H. R. Amber Shade C, No. 347 plus Corning Amethyst, No. 507. Thickness ratio 1 : 0.715	99 Amber
Bausch and Lomb, Amethyst Shade B plus Corning, H. R. Amber Shade A, No. 346. Thickness ratio 1 : 0.6	22 Amber
Fish-Schurman Corp., Pink Shade C	18 Amber
Fish-Schurman Corp., Pink Shade B	8 Amber

Certain shades of pink spectacle glass are available which have a smooth transmission curve from 400 to 700 millimicrons and produce a good color and energy match without need for further correction. These glasses are available in several densities. Fish-Schurman Pink Shade C is an excellent color temperature lowering filter of this type with a rating of about 18 mireds per mm. Fish-Schurman Pink Shade B rates about 8 mireds per mm. The denser of these glasses is shown in Fig. 8.

With the exception of Corning Daylite, the yellowish glasses, which lower color temperature, are somewhat more exact in converting the energy than are the bluish filters, although as mentioned before, the designed change in color is so small in the case of filters of low rating that small departures from the ideal color are of little consequence.

For convenience the characteristics of the filters just described have been assembled in Table II. By a suitable choice of filter components and of thickness a wide range of color temperature colors can be accurately matched and measured.

Annual Report of the Secretary of the Optical Society of America for the Calendar Year 1935

Membership Record

January 1, 1935 to January 1, 1936

	Honorary	Regular Annual Payment	Regular Life Payment	Associate Individual Annual Payment	Associate Corporation	Total
Membership as of record in the books of the Secretary and Treasurer 1–1–35	4	409	7	179	9	608
Losses during 1933 not previously reported						
By resignation as of 1–1–33	0	1–	0	1–	0	2–
Losses during 1934 not previously reported						
By death	0	0	0	1–	0	1–
By resignation as of 12–31–34	0	0	0	0	1–	1–
Gains during 1935						
By election during 1935 as of 1–1–35	0	0	0	24+	0	24+
Losses during 1935						
By death	0	3–	1–	0	0	4–
By resignation as of 1–1–35	0	3–	0	3–	0	6–
By separation for nonpayment of dues	0	9–	0	12–	0	21–
Membership as of record 12–31–35	4	393	6	186	8	597
Gains between 12–31–35 and 1–1–36						
By election during 1935 as of 1–1–36	0	0	0	20+	0	20+
By transfer 10–23–35 as of 1–1–36	0	16+	0	0	0	16+
Losses between 12–31–35 and 1–1–36						
By transfer 10–23–35 as of 1–1–36	0	0	0	16–	0	16–
By resignation during 1935 as of 12–31–35	0	3–	0	0	0	3–
Membership as of record 1–1–36	4	406	6	190	8	614

Resigned as of January 1, 1933 (not previously reported)

Evelyn C. Henderson (622 A)
Shirleigh Silverman (879 R)

Died in 1934 not reported until 1935

C. W. Robbins (686 A)

Resigned as of December 31, 1934 (not previously reported)

Munsell Research Laboratory (293 AC)

Elected during 1935 as of January 1, 1935

J. Stiles Beggs (987 A)
Haller Belt (989 A)
Kenneth Burgess (994 A)
Stuart Campbell (984 A)
Victor Chalupski (1008 A)
William A. E. Drescher (988 A)
James J. Glenn (991 A)
Arthur E. Jacobsen (1010 A)
James T. Killian (990 A)
Frederick L. Knowles (995 A)
Carl F. Lomb (979 A)
Alexander Boyd McLay (993 A)
H. B. Maris (986 A)
Charles A. Morrison (982 A)
Daniel Norman (1000 A)
Wm. J. O'Leary (999 A)
J. A. Scheick (978 A)
John M. Slater (976 A)
John F. Smith (983 A)
Joseph F. Taylor (985 A)
George E. Valley, Jr. (980 A)
Louis R. Weber (992 A)
H. Theodore Wensel (981 A)
Hans Wolfgang Zieler (977 A)

Elected during 1935 as of January 1, 1936

Wilmer C. Anderson (1009 A)
Ormond Barstow (1002 A)
William W. Bartlett (1004 A)
James R. Benford (997 A)
Harold M. Davis (1018 A)
Lee A. DuBridge (996 A)
Edmund A. Georgi (1016 A)
Geraldine W. Haupt (1005 A)
C. Earl Hays (1014 A)
Max Herzberger (1006 R)
H. Orlo Hoadley (1007 A)
Waldo H. Kliever (1013 A)
Roger P. Loveland (1001 A)
J. L. Michaelson (1003 A)
Oran E. Miller (1017 A)
Richard F. Morton (1011 A)
Leigh Page (998 R)
Walter T. Spry (1015 A)
Roy E. Thompson (1012 A)
Robert W. Vose (1019 A)

Elected to Regular Membership by Action of the Board of Directors, October 23, 1935, Effective January 1, 1936

Stuart Campbell (984 R)
Myrl N. Davis (959 R)
H. J. Eckweiler (860 R)
Max Herzberger (1006 R)
R. S. Hunter (947 R)
H. D. Judd (68 R)
L. C. Lewis (818 R)
H. B. Maris (986 R)
L. R. Maxwell (838 R)
H. Mestre (624 R)
Sidney Newhall (933 R)
R. D. Nutting (967 R)
Leigh Page (998 R)
W. W. Stifler (799 R)
H. T. Wensel (981 R)
H. W. Zieler (977 R)

Deaths during 1935

William Duane (208 R)
John C. McLennan (396 R)
M. I. Pupin (298 RL)
C. E. Mendenhall (150 R)

Resignations during 1935 as of January 1, 1935

Herbert J. Brennen (589 R)
S. N. Banerji (560 A)
Arthur Bramley (817 R)
H. B. Brooks (776 A)
Frederick A. May (751 A)
Walter P. White (364 R)

Resignations during 1935 as of December 31, 1935

Edwin C. Kemble (438 R)
Jean Jacque Weigle (432 R)
George Winchester (635 A)

(*Signed*) L. B. TUCKERMAN, *Secretary*

Optical Society of America, Inc.

Cash Transactions January 1, 1935 to December 31, 1935

Receipts

Dues	$3,034.59	
Dues in Advance	47.30	
Unbudgeted Income	119.10	
Local Committee Fund	138.76	
Interest on Bonds	565.44	
Interest on Bank Deposits	199.36	
Ives Medal Fund Income	16.56	
Adolph Lomb Memorial Fund Income	47.50	
Contributions	502.00	
Refunded Check Tax	0.08	
		$ 4,670.69

Disbursements

Secretary's Expense	$ 575.34	
Secretary's Travel Expense	48.98	
Treasurer's Expense	86.49	
Journal Publication Expense	750.00	
Journal Editorial and Office Expense	900.00	
Contingencies	195.27	
Purchase of Ives Medal	18.14	
Membership Committee	10.00	
Exchange Adjustment on 1934 Check	0.04	
		$ 2,584.26

Cash Increase January 1 to December 31, 1935	2,086.43
Cash in Bank January 1, 1935	8,182.45
Adolph Lomb Memorial Fund Principal	2,000.00
Total Cash on deposit January 1, 1936	$12,268.88

Ives Medal Fund

Income

Balance (including principal) January 1, 1935		$567.29
Interest—3 mo. on $500 Liberty bonds at 4¼%	$ 5.31	
9 mo. U. S. Treasury Certif. at 3%	11.25	16.56
		$583.85

Disbursements

Medal for George Ellery Hale	18.14
Balance Dec. 31, 1935	$565.71

Note:—The $500 U. S. Treasury Certificates is included in the bonds recorded in the Investment statement. The $65.71 balance of income is included in the cash transactions statement.

Adolph Lomb Memorial Fund

Balance January 1, 1935	$2,045.00
Bank Interest, 1935	47.50
Balance December 31, 1935	$2,092.50

Note:—The $92.50 accrued interest is included in the cash transactions statement.

1935 Journal Publication Account

Condensed Account Rendered by the American Institute of Physics

Receipts

Cash on hand January 1, 1935	$ 119.10	
Cash advanced by Optical Society	750.00*	
Cash on hand, earmarked for publication of Directory, received Dec. 31, 1934	400.00*	
Miscellaneous collections	24.28*	
		$1,293.38

Disbursements

Cash paid to Optical Society	$ 119.10	
Cost of back numbers of Journal	230.00	
Excess of Expense over Income in publication of J. O. S. A. for 1935	1,417.53*	
Institute of Physics Service Charge	1,097.86*	
		$2,864.49
Due the American Institute of Physics December 31, 1935		$1,571.11

	$ 750.00*
	400.00*
	24.28*
	1,417.53*
	1,097.86*
Total cost of publishing the journal during 1935, including the directory but not including the cost of back numbers	$3,689.67

1935 Optical Society Investments

	Control Value	Cost	Market, Nov. 15, 1935
$7000 Atchison Topeka & Santa Fe 4% Bonds	$ 7,000.00	$ 6,916.25	$ 7,595.00
$5600 U. S. Treasury Certificates 3¼% Due 1945	5,600.00	5,625.67	5,839.68
$8000 U. S. Treasury Certificates 3% Due 1948/6	8,000.00	8,261.30	8,197.20
	$20,600.00	$20,803.22	$21,631.88

Sale and Purchase Transaction

Sold $8000 Liberty Loan 4¼% Bonds of 1938, Called, at 100$\frac{25}{32}$—Proceeds less charges	$8,056.03
Bought $8000 U. S. Treasury Certificates 3% Due 1948 at 103$\frac{5}{32}$—Cost including charges	8,261.30
Net loss due to change	$ 105.27

(*Signed*) Henry F. Kurtz, *Treasurer*

February 10, 1936

The undersigned, having been duly appointed to audit the books of the treasurer of the Optical Society of America from January 1, 1935 to December 31, 1935, hereby CERTIFY that the treasurer's official report of receipts, disbursements and investments is correct as shown by records, bank statements, vouchers, etc.

(*Signed*) Carl L. Bausch
C. W. Frederick

Proceedings of the New York Meeting of the Optical Society of America

FEBRUARY 21 AND 22, 1936

JOINT MEETING WITH THE AMERICAN PHYSICAL SOCIETY

THE joint meeting of the Optical Society of America and the American Physical Society was held in New York City, February 21 and 22, 1936.

JOINT SYMPOSIUM ON THE DIFFRACTION GRATING

The principal feature of the meeting was the joint symposium of the two societies on Friday morning, February 21, devoted to invited papers on *The Diffraction Grating*. The following papers were presented:

1. **Early History of the Diffraction Grating.** KARL K. DARROW, *Bell Telephone Laboratories*
2. **On the Ruling and Testing of Diffraction Gratings.** R. W. WOOD, *Johns Hopkins University*
3. **Developments in the Rulings of Gratings at the University of Chicago.** HENRY G. GALE, *University of Chicago*
4. **Diffraction Grating Supply and Demand.** R. C. GIBBS, *Cornell University*

JOINT DINNER

On Friday evening, February 21, a joint dinner for the members of the two societies was held, with Professor F. K. Richtmyer, president of the Physical Society, presiding.

CONTRIBUTED PAPERS

Simultaneous meetings of the American Physical Society and the Optical Society of America for the reading of contributed papers were held on Friday afternoon, February 21. The authors' abstracts of the papers presented before the Optical Society of America are appended.

MEETING OF THE BOARD OF DIRECTORS

A meeting of the Board of Directors was held Thursday evening, February 20. Minutes of this meeting are appended.

L. B. TUCKERMAN, *Secretary*

Minutes of the Seventh Meeting of the Directors of the Optical Society of America, Incorporated

NEW YORK, N. Y., FEBRUARY 21, 1936

BESIDES the transaction of routine business the following items of general interest to members of the Society were taken up:

ANNOUNCEMENTS BY SECRETARY

Results of letter ballots:

Appointment of Committee on Meetings and Programs

George R. Harrison, *Chairman*
J. A. Anderson — Saul Dushman
Burt Carroll — E. D. Tillyer

Appointment of Committee on Finance

H. F. Kurtz, *Chairman*
C. L. Bausch — Edgar D. Tillyer
L. A. Jones — J. P. C. Southall
F. K. Richtmyer — T. R. Wilkins

Appointment of Committee on Honorary Members

W. E. Forsythe, *Chairman*
R. C. Gibbs — F. E. Wright

Appointment of Committee on Adolph Lomb Memorial Fund

J. P. C. Southall, *Chairman*
F. E. Wright — L. V. Foster

Appointment of Committee on Qualifications for Membership

W. E. Forsythe, *Chairman*
F. L. Mohler — J. S. Friedenwald
A. H. Pfund — L. O. Grondahl

Appointment of Committee to Consider Publication of Colorimetry Report

F. K. Richtmyer, *Chairman*
L. A. Jones — H. A. Barton

Appointment of Committee on Index

F. K. Richtmyer, *Chairman*
A. C. Hardy — R. C. Gibbs

Appointment of Auditors of Treasurer's Accounts

C. L. Bausch C. W. Frederick

Nomination of W. B. Rayton for Director of the American Institute of Physics. (Note: Elected Director by Governing Board, February 21, 1936.)

Appointment of Frank Benford as representative on the U. S. National Committee of the International Commission on Illumination.

Appointment of Representatives on the Inter-Society Color Council

L. A. Jones, *Chairman*

A. Ames, Jr.	A. E. O. Munsell
I. H. Godlove	A. H. Pfund
Deane B. Judd	W. B. Van Arsdel

Appointment of W. B. Rayton as representative of the Optical Society of America at the inauguration of Dr. Valentine as President of the University of Rochester.

Nomination and appointment of representatives:

Nomination of L. B. Tuckerman as representative on the Division of Physical Sciences, National Research Council, for a term to expire June 30, 1939. (Note: Elected Executive Member and member of the Executive Committee by the Division, May 3, 1936.)

Appointment of A. H. Pfund as representative on the Council of the American Association for the Advancement of Science, for a term to expire in February, 1938.

Appointment of A. C. Hardy as representative on the American National Committee on International Congresses on Photography, for a term to expire in October, 1938.

Appointment of E. D. Tillyer and H. F. Kurtz, as representative and alternate on A. S. A. Sectional Committee on Safety Code for Specifications and Methods of Test for Safety Glass—Z26, for a term to expire in October, 1937.

Appointments by the President:

Members of Committee on Membership under the chairmanship of W. B. Rayton

Haller Belt	Wm. Herriott
T. R. Wilkins	G. W. Moffitt
G. R. Harrison	W. E. Forsythe
Dorothy Nickerson	Roger S. Estey
L. W. Tilton	J. W. Beams

Committee on Colorimetry

L. A. Jones, *Chairman*

E. Q. Adams	Dorothy Nickerson	Brian O'Brien
Chas. Bittinger	M. R. Paul	I. H. Godlove
H. P. Gage	J. W. Forrest	W. T. Spry
K. S. Gibson	C. E. Foss	D. C. MacAdam
A. C. Hardy	E. C. Crittenden	W. B. Van Arsdel
D. B. Judd	Carl Z. Draves	M. Luckiesh
E. M. Lowry	Louise L. Sloan	

Voting delegates in the Inter-Society Color Council:

L. A. Jones I. H. Godlove

D. B. Judd

Membership

The Secretary's report showed a gratifying increase in membership, 27 new members having been elected since the October meeting.

Treasurer's Report

The report of the Treasurer showed that the financial status of the Society continued satisfactory.

Index to Journal

The Committee on Index to the journal reported that the copy for the index was expected to be ready for the printer about April 1.

It was voted that:

"One copy of the index be distributed without charge to members who pay their dues for the calendar year 1936"; and further voted that:

"Other copies of the index be sold at a price sufficient to cover the cost of manufacturing, handling, and mailing."

Joint Meeting of Member Societies

The plan of the American Institute of Physics for a joint meeting of all the five member societies in October was approved.

L. B. Tuckerman, *Secretary*

Program of Sessions for Contributed Papers

(TITLES AND ABSTRACTS* OF PAPERS)

The Estimation of Gloss with a Luminous Target. RICHARD S. HUNTER, *National Bureau of Standards.*

A target having a pattern of concentric rings varying from fine lines to broad bands has been placed in the open face of a desk lamp. This luminous target provides a reproducible source of light for the study of the gloss characteristics of the more glossy surfaces. The lines and bands of varying size in the target provide means for studying surfaces of a wide range of "sharpness-of-image" gloss. Records may be made of these lines and bands as they are reflected from different materials. Such records may be made to serve as permanent gloss values for the different surfaces studied. The dark areas of the target immediately adjacent to the luminous areas provide ideal conditions for the identification of surface "bloom." The best gloss differentiations are made when the lamp is used in a darkened room so that the luminous target is the only source of light to illuminate the surfaces being inspected. Photographic records of gloss and unusual gloss effects will be discussed.

Hunter, *A New Gloss Comparator*, Scientific Section Circular No. 493 of Nat. Paint, Varnish and Lacquer Assoc., Washington, D. C., Oct. 1935.
Hunter, *Identification of Five Different Types of Gloss Effects*, Paper presented before 20th Annual Meeting, O. S. A., Philadelphia, Oct. 1935.

Calibration and Use of a Subtractive Colorimeter for Small Chromaticity Differences on the Standard ICI System. DEANE B. JUDD, *National Bureau of Standards.*

The colorimeter is one previously[1] described in which the chromaticity of the comparison beam may be altered by adjustment of either of two pairs of double wedges, one of greenish, the other of yellowish glass. This colorimeter has been calibrated in terms of the ICI standard observer and coordinate system for colorimetry[2] for five comparison surfaces having Munsell notations approximately: N/10, P 6/3, PB 5/7, G 8/3, YRY 8/4. The details of calibration will be given for one comparison surface and the method of reducing data obtained will be illustrated by an example. Some results illustrative of the accuracy and reproducibility obtainable will be shown.

[1] D. B. Judd, *A Subtractive Colorimeter for the Measurement of Small Chromaticity Differences between Surfaces of Moderate Spectral Selectivity of Reflectance*, Paper 16, 20th Annual Meeting, O. S. A., Oct. 1935.
[2] D. B. Judd, J. O. S. A. **23**, 359 (1933).

The Design of Color Temperature Altering Filters. ROGER S. ESTEY, *Electrical Testing Laboratories, New York.*

Good color temperature altering filters must be able to convert energy having a black-body distribution into a new distribution which is still Planckian in character. The ability of a filter to convert accurately from one color temperature color to another can be determined by plotting the incident and transmitted light in trilinear coordinates on a mixture diagram which also carries the black body locus. In terms of reciprocal color temperature the color temperature altering interval of the filter is independent of the incident color temperature and depends only on the filter itself. This filter rating is proportional to the filter thickness and can be obtained from the mixture diagram.

FILTER COMPONENTS	C. T. INTERVAL (micro reciprocal degrees per mm)
Pittsburgh Plate Glass Co., Blue Plate	16 Blue
Corning Glass Works, Daylite No. 590	35 Blue
Corning Glass Works, Furnace Door Blue No. 533 plus Soft-Lite Lens Co., Soft-Lite No. 4. Thickness ratio 1 : 0.2.	65 Blue
Fish-Schurman Corp., Medium Shade Pink	8 Amber
Fish-Schurman Corp., Dark Shade Pink	16 Amber
Bausch and Lomb Optical Co., Amethyst Shade B plus Corning, H. R. Amber Shade C No. 347. Thickness ratio 1 : 0.2	30 Amber

If commercially available filters are unsatisfactory for some particular problem special filters can sometimes be designed by combining two or more glasses of selected thickness in cemented combination. The progress of the design can be observed by plotting the successive steps on the mixture diagram. The usual color temperature range is covered by filters of selected thickness taken from the table.

It is important that filters convert the energy correctly as well as the mere color. Filters will do this if their spectrophotometric curves are linear when plotted in the form logarithm of the transmission *versus* reciprocal of the wavelength. The slope of the best straight line through the data is proportional to the filter rating.

Deane B. Judd, "The 1931 I. C. I. Standard Observer and Coordinate System for Colorimetry," J. O. S. A. **23**, 359 (1933).
R. Davis and K. S. Gibson, "Filters for the Reproduction of Sunlight and Daylight and the Determination of Color Temperature," Bur. Stand. Misc. Pub. No. 114, January, 1931.
H. P. Gage, "Color Filters for Altering Color Temperature. Pyrometer Absorption and Daylite Glasses," J. O. S. A. **23**, 46 (1933).

Dark Adaptation as Influenced by Intensity of Light Adaptation. SELIG HECHT AND CHARLES HAIG, *Columbia University.*

We have measured the dark adaptation of a circular retinal area 5° in diameter, situated 30° nasally, after light adaptation to different intensities of white light. The light adapting field is circular and 30° in diameter; its center is situated 30° nasally; its brightness varies between 400 and 400,000 photons; exposure to it lasts 2 minutes.

With extreme violet light for measuring dark adaptation and a very low visual acuity for a threshold criterion, dark adaptation always shows two stages. The first begins at once; it is rapid, and the violet color is always evident at the threshold. The second stage begins only after a definite time; it is slower than the first, and shows no color at the threshold. The transition from the first to the second stage is sharp at the higher light adaptations and becomes more gradual as the adaptation intensity decreases. The intensity range covered by the two stages is nearly the same at the highest light adaptation, and decreases as the adaptation intensity decreases; the range of the first stage decreases much more rapidly than that of the second stage. The shape of the colorless second portion remains fairly constant for

* The abstracts were preprinted in the program subject to correction by the authors. Corrections that have been communicated to the secretary have been made in the abstracts here reprinted.

all subjects at all light adaptations; the colored first stage, however, changes in shape markedly, becoming faster with lower light adaptations. The colorless second stage appears earlier as the adapting intensity decreases; the time of appearance is a logarithmic function of the adapting intensity.

Similar measurements with extreme red light show mainly the colored primary stage of dark adaptation, and only the slightest indication of a colorless secondary stage. Thus the whole of dark adaptation measured with red light behaves to changes in light adaptation much as does the colored primary stage alone when violet measuring light is used.

We interpret these data to mean that the colored primary dark adaptation represents mainly the function of the cones, while the colorless secondary dark adaptation is a function of the rods.

The present paper will appear in full in Journal of General Physiology

Balanced Circuits Employing Barrier-layer Photoelectric Cells. R. H. MÜLLER AND A. SPECTOR, *New York University.*

Many circuits have been suggested recently for the utilization of barrier-layer cells in photometry. Their proponents have inferred that fluctuations in the light source are largely compensated by employing two cells, balanced in opposition. This is likely to be true where optical compensation is employed, but wherever electrical compensation is invoked difficulties may arise. This is particularly true for this type of cell, in which the short circuit current is a linear function of the intensity and the open circuit e.m.f. is a logarithmic function of the intensity.[1]

These circuits have been analyzed in detail and the optimum conditions for stability have been evaluated. The net response of the balanced arrangements has been studied and compared with the single cell method.

[1] R. H. Müller and G. F. Kinney, J. O. S. A. **25**, 342 (1935).
The present paper will appear in full in J. O. S. A.

Sextant wih Improved Filters. E. O. HULBURT, *Naval Research Laboratory.*

The navigator's sextant is usually equipped with two sets of filters, called the "celestial" filters and the "horizon" filters. Each set consists of three or four gray or colored glass filters any one or more of which can be put into position. A convenient filter has been devised whose optical transmission may be varied quickly and continuously to less than 1 percent. It consists of two polarizing plates, made of polarizing film mounted between glass with Balsam, arranged so that one may be rotated with respect to the other.

The celestial filter consists of two polarizing plates one or both of which may be interposed into the optical path, and when both are in position one may be rotated with respect to the other to yield the desired reduction in light intensity of the celestial object. Since the light from celestial objects is in general unpolarized the plates produce no special or unusual effects. They fulfill only the single function of providing a convenient and rapidly adjustable variable filter.

The horizon filter likewise consists of two polarizing plates. These, however, fulfill a double function. One plate is set with axis of polarization vertical; this usually sharpens the sea sky horizon because of the differential amount of polarization of the light from the sea and sky near the horizon; it also diminishes the glare of the sun path on the water.[1] The addition of the second plate, which is rotatable, provides a rapidly adjustable variable filter. In practice the second plate is seldom necessary.

[1] Hulburt, J. O. S. A. **24**, 35 (1934).

A New Theory of Optical Image Formation. MAX HERZBERGER, *Eastman Kodak Research Laboratory.*

A report including the generalization of the Gaussian theory of image formation with regard to an arbitrary ray; the location of points with a sharp image, and points whose image caustics are symmetrical; the derivation of the angle eiconal W for systems with certain special qualities; and a discussion of the qualities of ideal optical systems.

The present paper will appear in full in J. O. S. A.

Coloration of Lithium Fluoride by Glow Discharge and Some Practical Applications. EDWIN G. SCHNEIDER, *Harvard University.*

The coloration of lithium fluoride crystals by x-ray irradiation has been studied by R. Ottmer[1] and P. L. Bayley.[2] They report the production of absorption bands in the near ultraviolet with maxima at 2500A and 3100A, but no visible discoloration. Experiments on lithium fluoride exposed to strong extreme ultraviolet radiation or to glow discharge showed that these ultraviolet bands were developed. In addition a strong band with a maximum near 5200A appeared. The efficiency of production of the absorbing centers was very low for the extreme ultraviolet, a week of continuous exposure giving a slight yellow throughout the body of the crystal. Intense glow discharge turned a surface layer a deep red, about the color of a Wrattan F filter, in ten minutes. The absorption was so strong in a red colored crystal that no light below about 6000A could be seen through the crystal when a hand spectroscope was pointed directly at the sun. Measurements with a quartz spectrograph showed continuous absorption down to about 2200A. From this wave-length to about 1400A several percent of the light was transmitted. Another specimen treated with glow discharge until it was a light orange showed slight transmission in the near ultraviolet with a considerable increase in transparency to the extreme ultraviolet down to 1200A. These measurements suggest the possible use of lithium fluoride colored by glow discharge as a filter for the extreme ultraviolet.

Specimens kept for a year showed considerable weakening of the near ultraviolet absorption with much less change in the visible band, thus giving a filter transparent to a wide range of ultraviolet, but opaque over most of the visible.

The color may be removed and the original transmission restored by heating. Such treatment produces a faint luminescence.

Since crystals about the shade of a light K filter showed less than five percent change in the extreme ultraviolet transmission, the visible discoloration of lithium fluoride may be used as a warning that the specimen is becoming opaque.

[1] R. Ottmer, Zeits. f. Physik **46**, 798 (1927).
[2] P. L. Bayley, Phys. Rev. **24**, 495 (1924).